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17

Steam Engine Valves and Reversing Gears

Features

17.1. Introduction

The valves are used to control the steam which drives the piston of a reciprocating steam engine. The valves have to perform the four distinct operations on the steam used on one side (*i.e.* cover end) of the piston, as shown by the indicator diagram (also known as pressure-volume diagram) in Fig. 17.1. These operations are as follows:

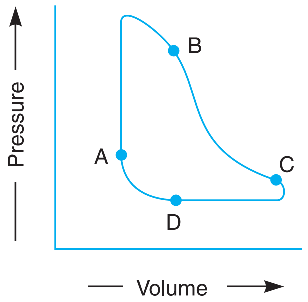

Fig. 17.1. Indicator diagram of a reciprocating steam engine.

1. *Admission* or opening of inlet valve for admission of steam to the cylinder. The point A represents the point for admission of steam just before the end of return stroke and it is continued up to the point B.

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2. *Cut-off* or closing of inlet valve in order to stop the admission of steam prior to expansion. The point *B* represents the cut-off point of steam. The curve *BC* represents the expansion of steam in the engine cylinder.

3. *Release* or opening of exhaust valve to allow the expanded steam to escape from the cylinder to the atmosphere or to the condenser or to a larger cylinder. The point *C* represents the opening of the valve for releasing the steam. The exhaust continues during the return stroke upto point *D*.

4. *Compression* or closing of exhaust valve for stopping the release of steam from the cylinder prior to compression. The point *D* represents the closing of exhaust valve. The steam which remains in the cylinder is compressed from *D* to *A* and acts as a cushion for the reciprocating parts.

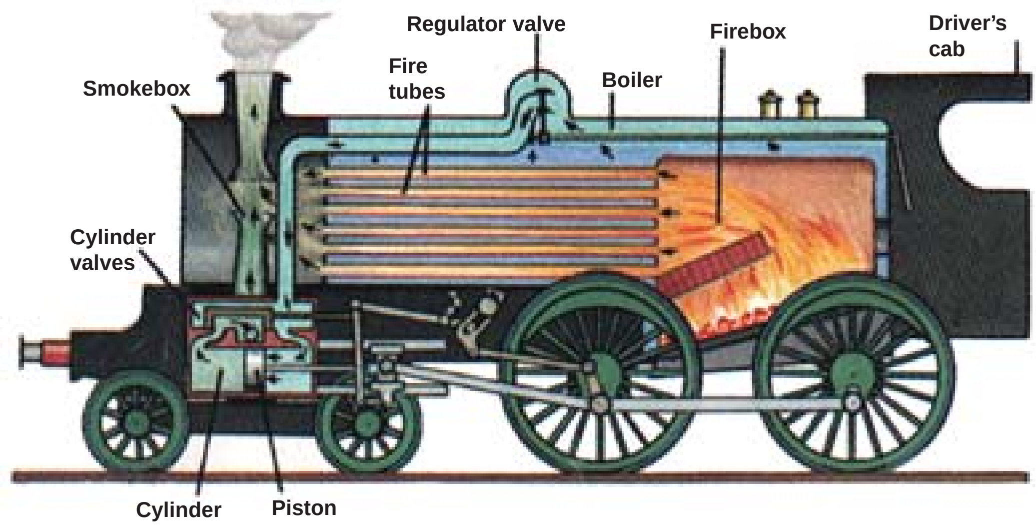
The same operations, as discussed above, are performed on steam in the same order on the other side (or crank end) of the piston for each cycle or each revolution of the crank shaft. In other words, for a double acting piston, there are eight valve operations per cycle. All these eight operations may be performed

(*i*) by a single slide valve such as *D*-slide valve,

(*ii*) by two piston valves, one for either end of cylinder, and

(*iii*) by two pairs of valves (one pair for each end of the cylinder), such as corliss valves or drop valves. One valve at each end of the cylinder performs the operations of admission and cut-off while the other valve performs the operations of release and compression.

The engine performance depends upon the setting of the valves. In order to set a valve at a correct position, a valve diagram is necessary.



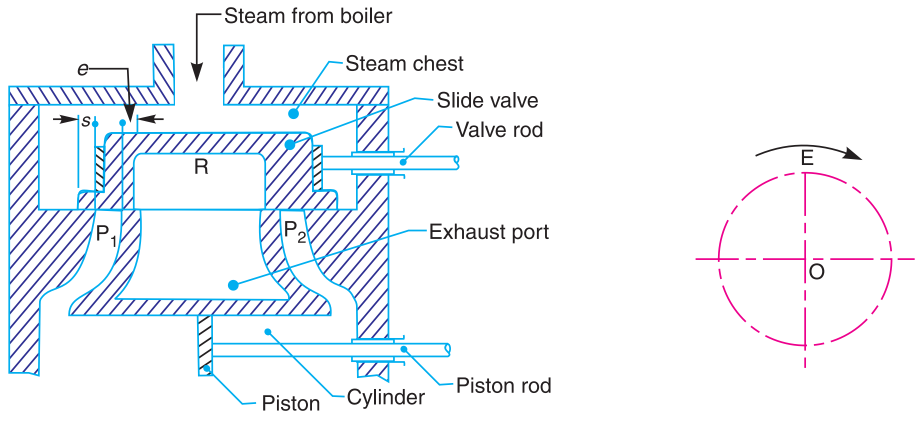
Sectional view of a steam engine.

17.2. D-slide Valve

The simplest type of the slide valve, called the *D*-slide valve, is most commonly used to control the admission, cut-off, release and compression of steam in the cylinder of reciprocating steam engine. The usual arrangement of the *D*-slide valve, valve chest and cylinder for a double acting steam engine is shown in Fig. 17.2 (*a*).

The steam from the boiler is admitted to the steam chest through a steam pipe. The recess *R* in the valve is always open to the exhaust port which, in turn, is open either to atmosphere or to the condenser. The ports P_1 and P_2 serve to admit steam into the cylinder or to pass out the steam from the cylinder. The valve is driven from an eccentric keyed to the crankshaft. It reciprocates across the ports and opens them alternately to admit high pressure steam from the steam chest and to exhaust the used steam, through recess *R* to exhaust port.

The *D*-slide valve in its mid position relative to the ports is shown in Fig. 17.2 (*a*). In this position, the outer edge of the valve overlaps the steam port by an amount *s*. This distance *s* (*i.e.* lapping on the outside of steam port) is called the ***steam lap or outside lap***. The inner edge of the valve, also, overlaps the steam port by an amount *e*. This distance *e* (*i.e.* overlapping on the inside) is called the ***exhaust lap or inside lap***.



(*a*) (*b*)

Fig. 17.2. *D*-slide valve.

The displacement of the valve may be assumed to take place with simple harmonic motion, since the *obliquity of the eccentric rod is very small. Thus the eccentric centre line *OE* will be at right angles to the line of stroke when the valve is in its mid-position. This is shown in Fig. 17.2 (*b*) for clockwise rotation of the crank.

Note: Since the steam is admitted from outside the steam chest, therefore the *D*-slide valve is also known as ***Outside admission valve***.

17.3. Piston Slide Valve

The piston slide valve, as shown in Fig. 17.3 (*a*), consists of two rigidly connected pistons. These pistons reciprocate in cylindrical liners and control the admission to, and exhaust from the two ends of the cylinder. In this case, high pressure superheated steam is usually admitted to the space between the two pistons through *O* and exhaust takes place from the ends of the valve chest through *E*. This type of valve is mostly used for locomotives and high pressure cylinders of marine engines. The piston slide valve has the following advantages over the *D*-slide valve :

* Since the length of the eccentric rod varies from 15 to 20 times the eccentricity (also known as throw of the eccentric), therefore the effect of its obliquity is very small. The **eccentricity** or the **throw of eccentric** is defined as the distance between the centre of crank shaft *O* and the centre of eccentric *E*. Thus the distance *OE* is the eccentricity.

1. Since there is no unbalanced steam thrust between the valve and its seat as the pressure on the two sides is same, therefore the power absorbed in operating the piston valve is less than the *D*-slide valve.

2. The wear of the piston valve is less than the wear of the *D*-slide valve.

3. Since the valve spindle packing is subjected to the relatively low pressure and temperature of the exhaust steam, therefore the danger of leakage is less.

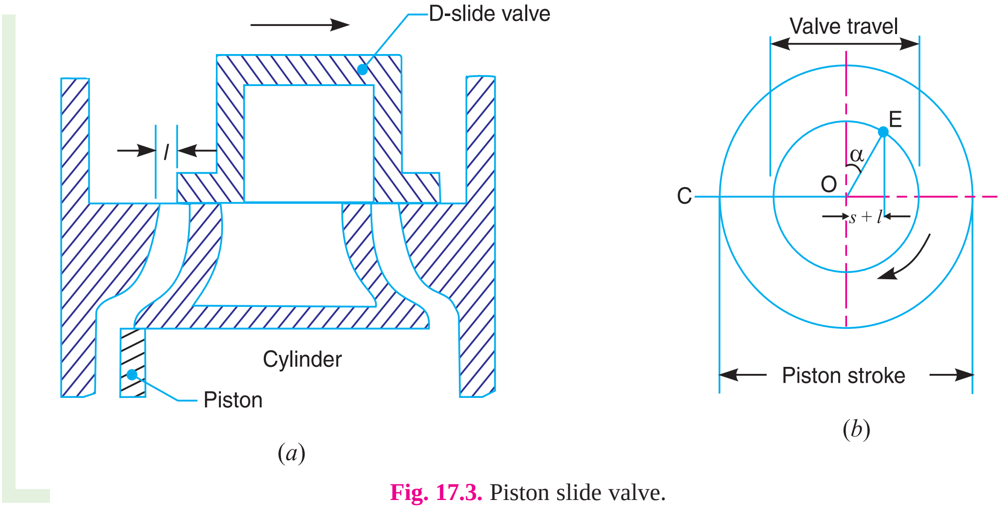


Fig. 17.3. Piston slide valve.

The position of the steam lap (s) and exhaust lap (e) for the piston valve in its mid position is shown in Fig. 17.3 (a). The eccentric position for the clockwise rotation of the crank is shown in Fig. 17.3(b).

Note: Since the steam enters from the inside of the two pistons, therefore the piston valve is also known as ***inside admission valve***.

17.4. Relative Positions of Crank and Eccentric Centre Lines

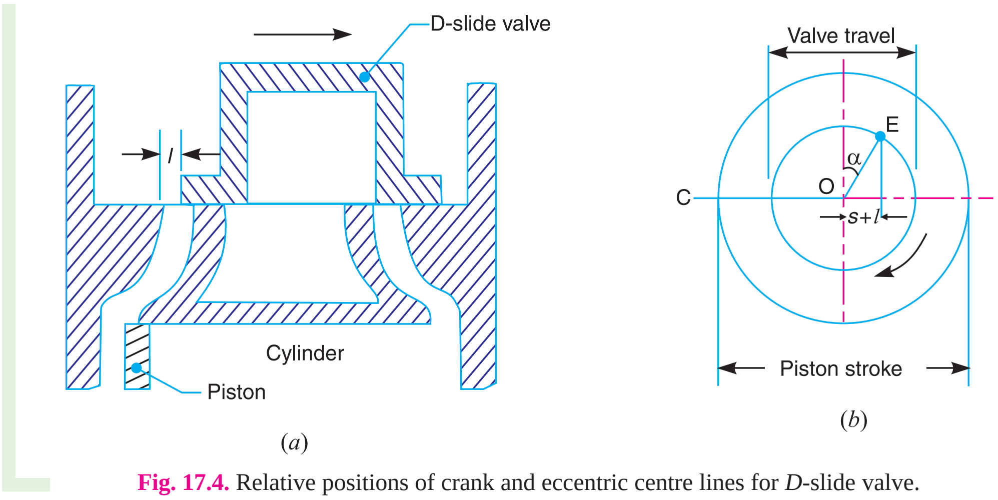


Fig. 17.4. Relative positions of crank and eccentric centre lines for *D*-slide valve.

We have discussed the *D*-slide valve (also known as outside admission valve) and piston slide valve (also known as inside admission valve) in Art. 17.2 and Art. 17.3 respectively. Now we shall discuss the relative positions of the crank and the eccentric centre lines for these slide valves.

1. *D-slide or outside admission valve*. The *D*-slide valve in its mid position is shown in Fig. 17.2 (*a*). At the beginning of the stroke of the piston from left to right as shown in Fig. 17.4 (*a*), the crank *OC* is at its inner dead centre position as shown in Fig. 17.4 (*b*). A little consideration will show that the steam will only be admitted to the cylinder if the *D*-slide valve moves from its mid position towards the right atleast by a distance equal to the steam lap (*s*). It may be noted that if only this minimum required distance is moved by the valve, then the steam admitted to the cylinder will be subjected to severe throttling or wire drawing. Therefore, in actual practice, the displacement of the *D*-slide valve is greater than the steam lap (*s*) by a distance *l* which is known as the ***lead*** of the valve.

In order to displace the valve from its mid position by a distance equal to steam lap plus lead (*i.e.* $s + l$), the eccentric centre line must be in advance of the 90° position by an angle α, such that

$$\sin \alpha = \frac{s + l}{OE}$$

The angle α is known as the ***angle of advance*** of the eccentric. The relative positions of the crank *OC* and the eccentric centre line *OE* remain unchanged during rotation of the crank *OC*, as shown in Fig. 17.4 (*b*).

Note : The eccentricity (or throw of the eccentric) *OE* is equal to half of the valve travel. The valve travel is the distance moved by the valve from one end to the other end.

2. *Piston slide valve or inside admission valve.* The piston slide valve in its mid position is shown in Fig. 17.3 (*a*). At the beginning of the outward stroke of the piston, from left to right as shown in Fig. 17.5 (*a*), the crank *OC* is at its inner dead centre as shown in Fig. 17.5 (*b*). In the similar way as discussed for *D*-slide valve, the valve should be displaced from its mean position by a distance equal to the steam lap plus lead (*i.e.* $s + l$) of the valve. The relative positions of the crank *OC* and the eccentric centre line *OE* are as shown in Fig. 17.5 (*b*). In this case, the angle of advance is (180° + α), and

$$\sin \alpha = \frac{s + l}{OE}$$

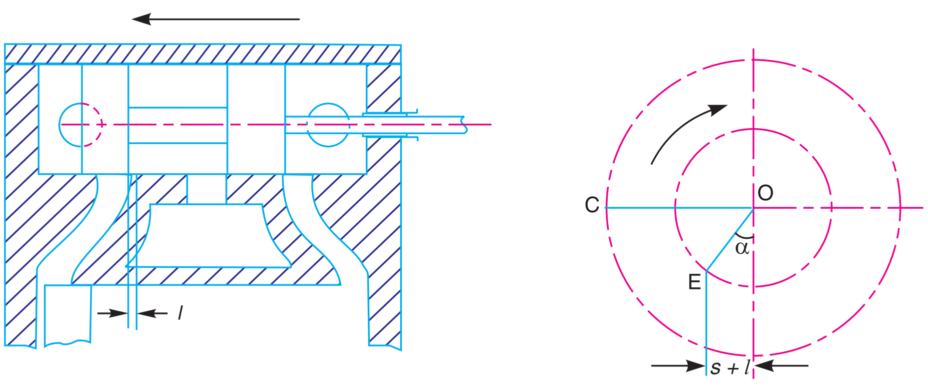


Fig. 17.5. Relative positions of crank and eccentric centre lines for piston slide valve.

17.5. Crank Positions for Admission, Cut-off, Release and Compression

In the previous article, we have discussed the relative positions of the crank and eccentric centre lines for both the *D*-slide valve and piston slide valve. Here we will discuss only the *D*-slide valve to mark the positions of crank for admission, cut-off, release and compression. The same principle may be applied to obtain the positions of crank for piston slide valve.

1. *Crank position for admission*. At admission for the cover end of the cylinder, the outer edge of the *D*-slide valve coincides with the outer edge of the port P_1. The valve moves from its mid position towards right, as shown by arrow *A* in Fig. 17.6 (*a*), by an amount equal to steam lap *s*. At the same time, the piston moves towards left as shown by thick lines in Fig. 17.6 (*a*). The corresponding position of the crank is OC_1 and the eccentric centre line is shown by OE_1 in Fig. 17.6 (*b*), such that

$$\angle C_1\, OE_1 = 90° + \alpha$$

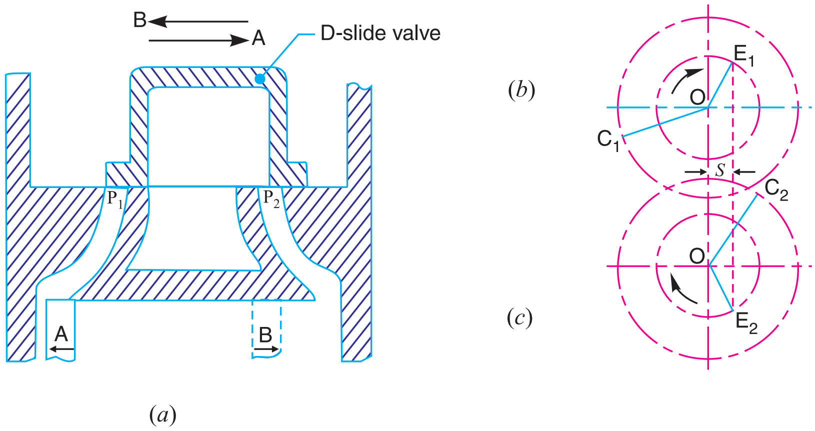


Fig. 17.6. Crank positions for admission and cut-off.

2. *Crank position for cut-off*. A little consideration will show that the cut-off will occur on the cover end of the cylinder when the outer edge of the *D*-slide valve coincides with the outer edge of the port P_1 while the valve moves towards left as shown by arrow *B*. The piston now occupies the position as shown by dotted lines in Fig. 17.6 (*a*). The corresponding position of the crank is OC_2 and the eccentric centre line is shown by OE_2 in Fig. 17.6 (*c*), such that

$$\angle C_2OE_2 = \angle C_1OE_1 = 90° + \alpha$$

3. *Crank position for release*. At release for the cover end of the cylinder, the inner edge of the *D*-slide valve coincides with the inner edge of the port P_1. The valve moves from its mid position towards left, as shown by arrow *C* in Fig. 17.7 (*a*), by a distance equal to the exhaust lap *e*. Thus the

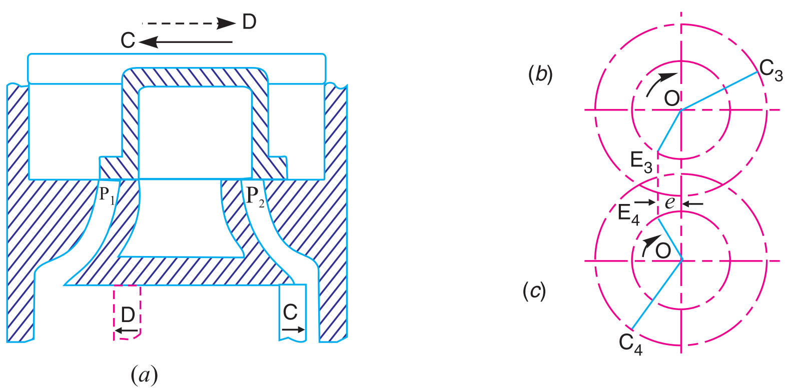


Fig. 17.7. Crank positions for release and compression.

valve opens the port to exhaust. At the same time, the piston moves towards right as shown by thick lines in Fig. 17.7 (*a*). The corresponding positions of crank and eccentric centre line are shown by OC_3 and OE_3 in Fig. 17.7 (*b*), such that

$$\angle C_3OE_3 = 90° + \alpha$$

4. *Crank position for compression*. At compression, for the cover end of the cylinder, the inner edge of the valve coincides with the inner edge of the port P_1. The valve moves from its mid position towards right, as shown by arrow *D* in Fig. 17.7 (*a*), by a distance equal to the exhaust lap *e*. The valve now closes the port to exhaust. The piston moves towards left as shown by dotted lines in Fig. 17.7 (*a*). The corresponding positions of crank and eccentric centre line are shown by OC_4 and OE_4 in Fig. 17.7 (*c*), such that

$$\angle C_4OE_4 = \angle C_3OE_3 = 90° + \alpha$$

The positions of crank and eccentric centre line for all the four operations may be combined into a single diagram, as shown in Fig. 17.8 (*a*). Since the ideal indicator diagram, as shown in Fig. 17.8 (*b*), is drawn by taking projections from the crank positions, therefore the effect of the obliquity of the connecting rod is neglected.

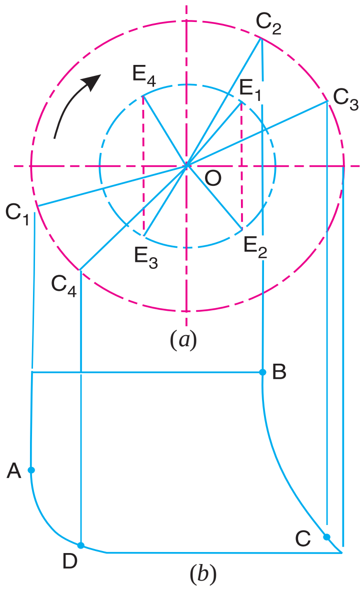
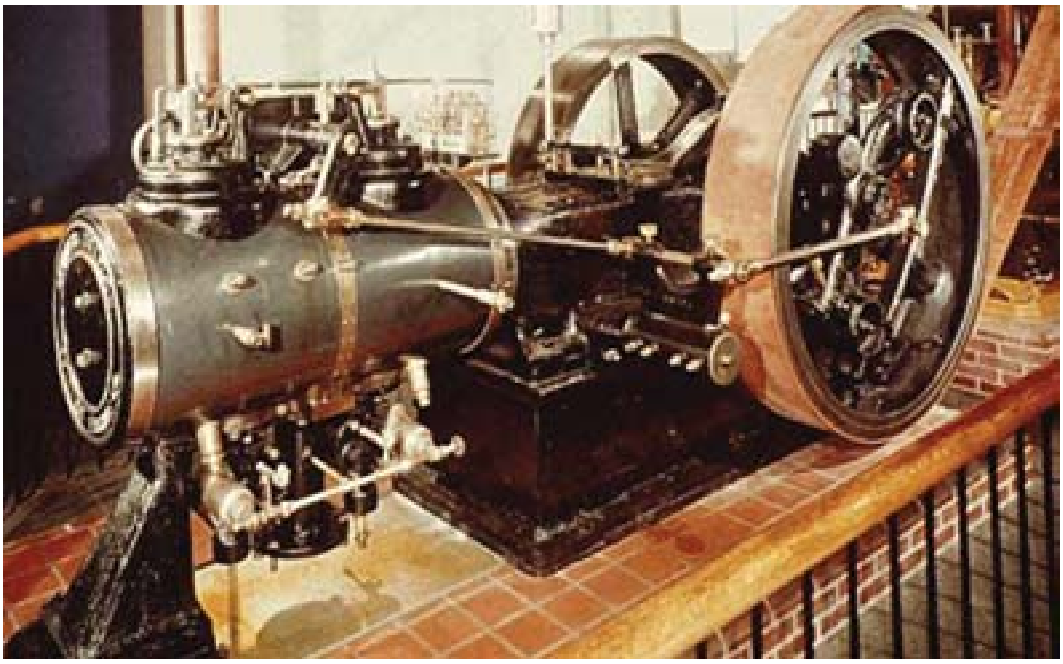


Fig. 17.8. Combined diagram of crank positions.



17.6. Approximate Analytical Method for Crank Positions at Admission, Cut-off, Release and Compression

The crank positions at which admission, cut-off, release and compression occur may be obtained directly by analytical method as discussed below :

Let x = Displacement of the valve from its mid-position,

θ = Crank angle,

r = Eccentricity or throw of eccentric $= \frac{1}{2} \times$ Travel of valve,

α = Angle of advance of eccentric.

Since the displacement of the valve may be assumed to take place with simple harmonic motion, therefore

$$x = r \sin(\theta + \alpha) \quad \ldots (i)$$

But at admission and cut-off,

$$x = \text{Steam lap}, s$$

$$\therefore \quad s = r \sin(\theta + \alpha) \quad \ldots\text{[From equation } (i)]$$

or
$$\theta + \alpha = \sin^{-1}\left(\frac{s}{r}\right), \text{ and } \theta = \sin^{-1}\left(\frac{s}{r}\right) - \alpha \quad \ldots (ii)$$

The two values of θ which satisfy the equation *(ii)* give the crank positions for admission and cut-off.

Similarly, at release and compression, x = exhaust lap (e) and is negative as measured from the origin O.

$$\therefore \quad -e = r \sin(\theta + \alpha) \quad \ldots\text{[From equation } (i)]$$

or
$$\theta + \alpha = \sin^{-1}\left(\frac{-e}{r}\right), \text{ and } \theta = \sin^{-1}\left(\frac{-e}{r}\right) - \alpha \quad \ldots (iii)$$

The two values of θ which satisfy the equation *(iii)* give the crank positions for release and compression.

Example 17.1. *The D-slide valve taking steam on its outside edges has a total travel of 150 mm. The steam and exhaust laps for the cover end of the cylinder are 45 mm and 20 mm respectively. If the lead for the cover end is 6 mm, calculate the angle of advance and determine the main crank angles at admission, cut-off, release and compression respectively for the cover end. Assume the motion of the valve as simple harmonic.*

Solution. Given : $2r = 2\,OE = 150$ mm or $r = OE = 75$ mm ; $s = 45$ mm ; $e = 20$ mm ; $l = 6$ mm

Angle of advance

Let α = Angle of advance.

We know that

$$\sin\alpha = \frac{s + l}{OE} = \frac{45 + 6}{75} = 0.68$$

or $\alpha = 42.8°$ **Ans.**

Crank angles at admission, cut-off, release and compression

Let

$\theta_1, \theta_2, \theta_3$ and θ_4 = Crank angles at admission, cut-off, release and compression respectively.

We know that for admission and cut-off,

Prototype of an industrial steam engine.

$$\theta + \alpha = \sin^{-1}\left(\frac{s}{r}\right) = \sin^{-1}\left(\frac{45}{75}\right) = \sin^{-1}(0.6) = 36.87° \text{ or } 143.13°$$

$\therefore \quad \theta_1 = 36.87° - \alpha = 36.87° - 42.8° = -5.93°$ **Ans.**

and $\quad \theta_2 = 143.13° - \alpha = 143.13° - 42.8° = 100.33°$ **Ans.**

We know that for release and compression,

$$\theta + \alpha = \sin^{-1}\left(\frac{-e}{r}\right) = \sin^{-1}\left(\frac{-20}{75}\right) = \sin^{-1}(-0.2667)$$

$$= 195.47° \text{ or } 344.53°$$

$\therefore \quad \theta_3 = 195.47° - \alpha = 195.47° - 42.8° = 152.67°$ **Ans.**

and $\quad \theta_4 = 344.53° - \alpha = 344.53° - 42.8° = 301.73°$ **Ans.**

17.7. Valve Diagram

The crank positions for admission, cut-off, release and compression may be easily determined by graphical constructions known as ***valve diagrams***. There are various methods of drawing the valve diagrams but the following three are important from the subject point of view :

1. Zeuner valve diagram. **2.** Reuleaux valve diagram, and **3.** Bilgram valve diagram.

We shall discuss these valve diagrams, in detail as follows.

17.8. Zeuner Valve Diagram

The Zeuner's valve diagram, as shown in Fig. 17.9, is drawn as discussed in the following steps :

1. First of all, draw AB equal to the travel of the valve to some suitable scale. This diameter AB also represents the stroke of the piston to a different scale.

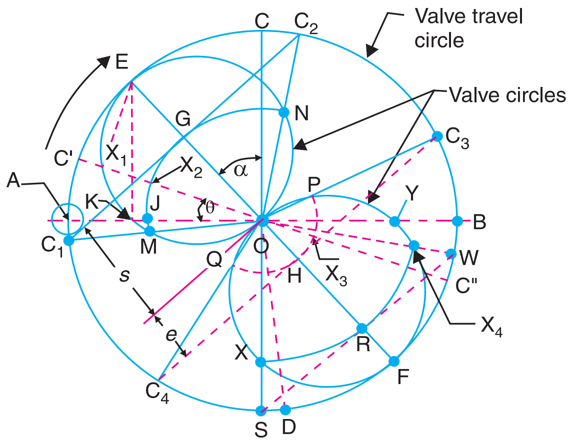


Fig. 17.9. Zeuner valve diagram.

2. Draw a circle on the diameter AB such that $OA = OB$ = eccentricity or throw of the eccentric. The circle $ACBD$ is known as the ***valve travel circle***, where diameter CD is perpendicular to AB.

3. Draw EOF making an angle α, the angle of advance of the eccentric, with CD. It may be noted that the angle α is measured from CD in the direction opposite to the rotation of the crank and eccentric as marked by an arrow in Fig. 17.9.

4. In case the angle of advance (α) is not given, then mark OJ = steam lap (s), and JK = lead (l) of the valve. Draw KE perpendicular to AB which intersects the valve travel circle at E. The angle EOC is now the angle of advance.

5. Draw circles on *OE* and *OF* as diameters. These circles are called ***valve circles***.

6. With *O* as centre, draw an arc of radius *OG* equal to steam lap (*s*) cutting the valve circle at *M* and *N*. Join *OM* and *ON* and produce them to cut the valve travel circle at C_1 and C_2 respectively. Now OC_1 and OC_2 represent the positions of crank at admission and cut-off respectively.

Note : The circle with centre *A* and radius equal to lead (*l*) will touch the line $C_1 C_2$.

7. Again with *O* as centre, draw an arc of radius *OH* equal to exhaust lap (*e*) cutting the valve circle at *P* and *Q*. Join *OP* and *OQ* and produce them to cut the valve travel circle at C_3 and C_4 respectively. Now OC_3 and OC_4 represent the position of crank at release and compression respectively.

8. For any position of the crank such as *OC′*, as shown in Fig. 17.9, the distance OX_1 represents the displacement of the valve from its mid position and the distance $X_1 X_2$ (the point X_1 is on the valve circle and the point X_2 is on the arc *JGN*) gives the opening of the port to steam. The distance $X_3 X_4$ (point X_3 is on the arc *QHP* and point X_4 is on the valve circle) obtained by producing the crank *OC′*, gives the opening of the port to exhaust for the crank position *OC′*. The proof of the diagram is as follows :

Join EX_1. Now angle $EX_1O = 90°$.

$$\therefore \angle OEX_1 + \angle X_1OE = 90° = \angle AOC = \theta + \angle X_1OE + \alpha$$

or $$\angle OEX_1 = \theta + \alpha$$

Now from triangle OEX_1,

$$OX_1 = OE \sin(\theta + \alpha)$$

or $$x = r \sin(\theta + \alpha)$$

where x = Displacement of the valve from its mid position, and

r = Eccentricity or throw of eccentric.

Now $$OX_1 = OX_2 + X_1 X_2$$

∴ Opening of port to steam when the valve has moved a distance *x* from its mid-position,

$$X_1 X_2 = OX_1 - OX_2 = r \sin(\theta + \alpha) - s \qquad ...(\because OX_2 = \text{Steam lap, } s)$$

9. Mark *HR* = width of the steam port. Now with *O* as centre, draw an arc through *R* intersecting the valve circle at *X* and *Y*. The lines *OS* and *OW* through *X* and *Y* respectively determines the angle *WOS* through which the crank turns while the steam port is full open to exhaust. The maximum opening of port to exhaust is *HF*. A similar construction on the other valve circle will determine the angle through which the crank turns while the steam port is not full open to steam. Fig. 17.9 shows that the steam port is not full open to steam and the maximum opening of the port to steam is *GE*.

Note : The valve diagram, as shown in Fig. 17.9, is for the steam on the cover end side of the piston or for one-half of the *D*-slide valve. In order to draw the valve diagram for the crank end side of the piston (or the other half of the valve), the same valve circles are used but the two circles and the lines associated with them change places. For the sake of clearness, the valve diagrams for the two ends of the piston is drawn separately.

17.9. Reuleaux's Valve Diagram

The Reuleaux's valve diagram is very simple to draw as compared to the Zeuner's valve diagram. Therefore it is widely used for most problems on slide valves. The Reuleaux's valve diagram, as shown in Fig. 17.10, is drawn as discussed in the following steps :

1. First of all, draw *AB* equal to the travel of the valve to some suitable scale. This diameter *AB* also represents the stroke of the piston to a different scale.

2. Draw a circle on the diameter *AB* such that *OA* = *OB* = eccentricity or throw of the eccentric. This circle *ACBD* is known as valve travel circle where diameter *CD* is perpendicular to *A B*.

3. Draw *EOF* making an angle α, the angle of advance of eccentric, with *CD*. It may be noted that the angle α is measured from *CD* in the direction opposite to the rotation of crank and eccentric as marked by an arrow in Fig. 17.10.

4. Draw *GOH* perpendicular to *EOF*. Now draw chords $C_1 C_2$ and $C_3 C_4$ parallel to *GH* and at distances equal to steam lap (*s*) and exhaust lap (*e*) from *GH* respectively.

5. Now OC_1, OC_2, OC_3 and OC_4 represent the positions of crank at admission, cut-off, release and compression respectively.

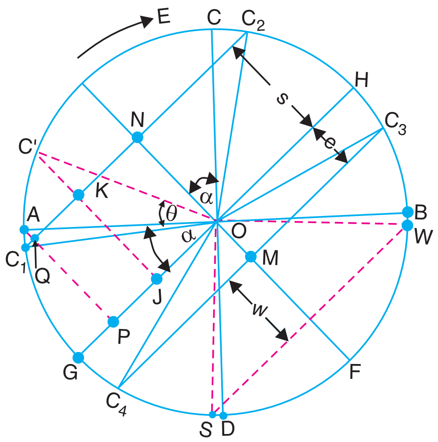


Fig. 17.10. Reuleaux's valve diagram.

The proof of the diagram is as follows :

Let *OC'* be any crank position making an angle θ with the inner dead centre, as shown in Fig.17.10. Draw *C' J* perpendicular to *GH*. From right angled triangle *OC' J*,

$$C'J = C'O \sin C'OJ = r \sin(\theta + \alpha) \qquad \text{...}(i)$$

where $r = C'O$ = Eccentricity or throw of eccentric.

But the displacement of the valve from its mid-position corresponding to crank angle θ is given by

$$x = r \sin(\theta + \alpha) \qquad \text{...}(ii)$$

From equations (*i*) and (*ii*),

$$C'J = x$$

It, therefore, follows that the length of the perpendicular from *C'* to the diameter *GH* is equal to the displacement of the valve from mid-position when the crank is in the position *OC'*.

We see from Fig. 17.10, that when the crank is in position OC_1 or OC_2, the length of the perpendicular from C_1 or C_2 on *GH* is equal to the steam lap (*s*). Therefore OC_1 and OC_2 must represent the crank positions at admission and cut-off respectively. Similarly, when the crank is in position OC_3 and OC_4, the length of perpendicular from C_3 or C_4 on *GH* is equal to the exhaust lap (*e*). Therefore OC_3 and OC_4 must represent the crank positions at release and compression respectively.

Opening of the port to steam

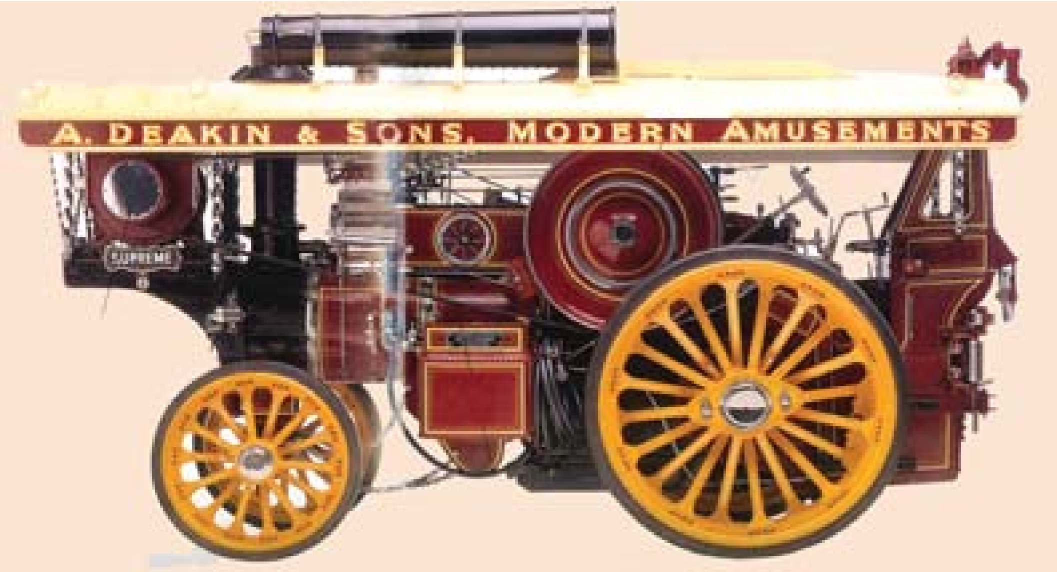
We see from Fig. 17.10, that when the crank is in position *OC'*, the displacement of the valve *C'J*, from its mid-position, exceeds the steam lap (*s*) by a distance *C' K*. The distance *C' K* represents the amount of port opening to steam. Therefore when the crank is in position *OA* (*i.e.* at the inner dead centre), the perpendicular distance from *A* to *GH*, *i.e. AP* represents the displacement of the valve from its mid-position. The distance *AP* exceeds the steam lap (*s*) by a distance *AQ* which is equal to the lead of valve and represents the amount of port opening to steam.

The maximum possible opening of the port to steam is equal to *NE i.e.* (*r*–*s*) where *r* is the throw of the eccentric or half travel of the valve and *s* is the steam lap. Similarly, the maximum possible opening of the port to exhaust is equal to *MF i.e.* (*r*–*e*) where *e* is the exhaust lap. The difference (*r*–*e*) may exceed the width of the actual port through which the steam is admitted to and exhausted from the cylinder. In that case, the port will remain fully open for a certain period of crank rotation. In order to find the duration of this period, draw a chord *S W* parallel to C_3C_4 at a distance equal to the width of the steam port (*w*). The port will remain fully open to exhaust when the crank rotates from the positon *O W* to *OS*.

17.10. Bilgram Valve Diagram

The Bilgram valve diagram, as shown in Fig. 17.11, is drawn as discussed in the following steps :

1. First of all, draw *A B* equal to the travel of the valve to some suitable scale. This diameter *A B* also represents the stroke of the piston to a different scale.



A 1930's Steam locomotive.

2. Draw a circle on the diameter *A B* such that *O A* = *OB* = eccentricity or throw of the eccentric. This circle is known as valve travel circle.

3. Draw diameter *GOH* making an angle α, the angle of advance, with *A B*. The angle α is measured from *A B* in the direction opposite to the rotation of crank and eccentric as marked by an arrow in Fig. 17.11.

4. Draw two circles with centres *G* and *H* and radii equal to steam lap (*s*) and exhaust lap (*e*) respectively as shown in Fig. 17.11.

5. The lines OC_1 and OC_2 are tangential to the steam lap circles and they represent the crank positions for admission and cut-off respectively. Similarly OC_3 and OC_4 are tangential to the exhaust lap circles and represent the crank positions for release and compression.

The proof of the diagram is as follows :

Let *OC'* be any crank position making an angle θ with the inner dead centre, as shown in Fig. 17.11. Draw perpendiculars *GE* on *OC'* and *HF* on *OC'* produced.

Since the triangles *OGE* and *OHF* are similar, therefore

$$GE = HF = OG \sin(\theta + \alpha) = r \sin(\theta + \alpha) \quad ...(i)$$

where $r = OG$ = Eccentricity or throw of eccentric.

But the displacement of the valve from its mid-position corresponding to crank angle θ, is given by

$$x = r \sin(\theta + \alpha) \quad ...(ii)$$

From equations **(*i*)** and **(*ii*),**

$$GE = x$$

It, therefore, follows that the length of the perpendicular from *G* (or *H*) on *OC′* (or *OC′* produced) is equal to the displacement of the valve from mid-position when the crank is in the position *OC′*.

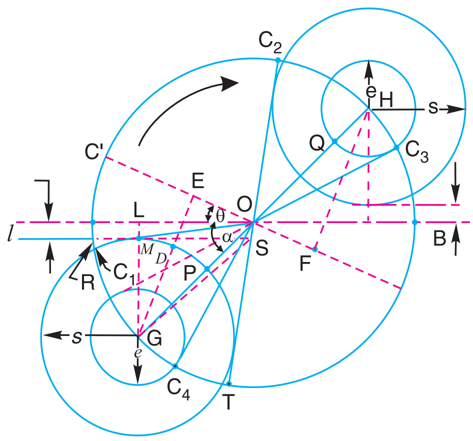


Fig. 17.11. Bilgram valve diagram.

We see from Fig. 17.11, that the length of the perpendiculars from *G* and *H* on OC_1 and OC_2 respectively are equal to steam lap (*s*). Therefore OC_1 and OC_2 must represent the crank positions at admission and cut-off respectively, Similarly, the length of perpendiculars from *H* and *G* on OC_3 and OC_4 respectively are equal to exhaust lap (*e*). Therefore OC_3 and OC_4 must represent the crank positions at release and compression respectively.

Opening of the port to steam

We see from Fig. 17.11, that when the crank is in position *OC′*, the displacement of the valve *GE*, from its mid-position, exceeds the steam lap (*s*) by a distance *DE*. The distance *DE* represents the amount of port opening to steam. Therefore, when the crank is in position *OA* (*i.e.* at the inner dead centre), the perpendicular distance from *G* to *OA* (*i.e. GL*) represents the displacement of the valve from its mid-position. The distance *GL* exceeds the steam lap (*s*) by a distance *ML* which is equal to lead of the valve and represents the amount of port opening to steam.

The maximum opening of the port to steam is equal to *OP* or $(r - s)$ where *r* is the throw of eccentric or half travel of the valve and *s* is the steam lap. Similarly the maximum opening of the port to exhaust is *OQ* or $(r - e)$ where *e* is the exhaust lap.

Notes : 1. The point *G* lies on the intersection of the bisectors of angles C_1OT and *RST*.

2. The Bilgram valve diagram is usually used to determine throw of the eccentric, valve travel, angle of advance of the eccentric, steam and exhaust laps when the crank positions at cut-off and release, lead of valve and width of steam port are known.

Example 17.2. *The following particulars refer to a D-slide valve :*

Total valve travel = 150 mm ; Steam lap = 45 mm ; Exhaust lap = 20 mm ; Lead = 6 mm.

Draw the Zeuner's valve diagram for the cover end and determine the angle of advance of the eccentric, main crank angles at admission, cut-off, release and compression, opening of port to steam for 30° of crank rotation and maximum opening of port to steam. If the width of the port is 40 mm, determine the angle through which the crank turns so that the exhaust valve is full open.

Solution. Given : $AB = 150$ mm ; $s = 45$ mm ; $e = 20$ mm ; $l = 6$ mm

Angle of advance of eccentric and main crank angles at admission, cut-off, release and compression

The Zeuner's valve diagram for the cover end is drawn as discussed in the following steps :

1. First of all draw AB = 150 mm, to some suitable scale, to represent the total valve travel. Draw a circle on this diameter AB such that $OA = OB$ = throw of the eccentric. This circle is known as valve travel circle. Draw COD perpendicular to AB.

2. Mark OJ = steam lap = 45 mm, and JK = lead = 6 mm. Through K, draw a perpendicular on AB which intersects the valve travel circle at E. Join OE. Now angle COE represents the angle of advance of the eccentric (α) in a direction opposite to the direction of rotation of crank and eccentric (shown clockwise in Fig. 17.12). By measurement, we find that

$$\alpha = \angle COE = 42.5° \textbf{ Ans.}$$

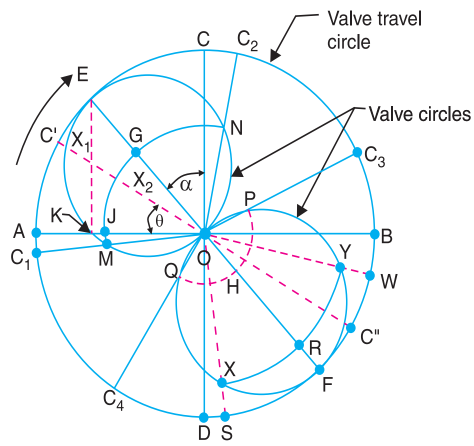


Fig. 17.12

3. Draw a circle on OE as diameter. This circle is known as valve circle. Now with O as centre, draw an arc of radius equal to steam lap (*i.e.* 45 mm) which intersects the valve circle at M and N. Join OM and ON and produce them to intersect the valve travel circle at C_1 and C_2 respectively. The lines OC_1 and OC_2 represent the crank positions at admission and cut-off respectively. By measurement, we find that

Crank angle at admission from inner dead centre A

$$= \angle AOC_1 = -6° \textbf{ Ans.}$$

and crank angle at cut-off from inner dead centre A

$$= \angle AOC_2 = 101° \textbf{ Ans.}$$

4. Now draw the diameter EOF. On OF draw a valve circle as shown in Fig. 17.12. With O as centre, draw an arc of radius equal to exhaust lap (*i.e.* 20 mm) which intersects the valve circle at P and Q. Join OP and OQ and produce them to intersect the valve travel circle at C_3 and C_4 respectively. Now OC_3 and OC_4 represent the crank positions at release and compression respectively. By measurement, we find that

Crank angle at release from inner dead centre A

$$= \angle AOC_3 = 153° \textbf{ Ans.}$$

and crank angle at compression from inner dead centre A

$$= \angle AOC_4 = 302° \textbf{ Ans.}$$

Opening of port to steam for 30° of crank rotation and maximum opening of port to steam

Let OC' be the crank at $\theta = 30°$ from the inner dead centre, as shown in Fig. 17.12. The crank

OC' intersects the valve circle at X_1 and arc MGN at X_2. Now $X_1 X_2$ represents the opening of port to steam for 30° of crank rotation. By measurement, we find that

$$X_1X_2 = 27 \text{ mm } \textbf{Ans.}$$

and maximum opening of port to steam,

$$GE = 30 \text{ mm } \textbf{Ans.}$$

Angle through which the crank turns so that the exhaust valve is full open

Mark HR = width of port = 40 mm as shown in Fig. 17.12. Now with O as centre, draw an arc passing through R which intersects the valve circle at X and Y. The angle XOY represents the crank angle at which the exhaust valve is full open. By measurement, we find that

$$\angle XOY = 72° \textbf{ Ans.}$$

Example 17.3. *The following data refer to a D-slide valve :*

Total valve travel = 120 mm ; Angle of advance = 35° ; Steam lap = 25 mm ; Exhaust lap = 8 mm.

If the length of the connecting rod is four times the crank radius, determine the positions of the piston as percentage of the stroke for admission, cut-off, release and compression for both ends of the piston.

Solution. Given : AB = 120 mm ; α = 35°, s = 25 mm ; e = 8 mm

Positions of the piston as a percentage of the stroke for admission, cut-off, release and compression for cover end of the piston.

First of all, determine the crank positions for the cover end either by Zeuner's or Reuleaux valve diagram. The Reuleaux valve diagram for the cover end, as shown in Fig. 17.13, is drawn as follows :

1. Draw AB = 120 mm to some suitable scale to represent the total valve travel. This diameter AB also represents the stroke of the piston. Draw a circle on diameter AB such that $OA = OB$ = Throw of the eccentric or radius of crank.

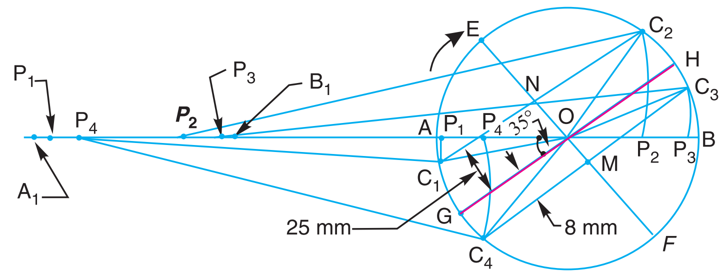


Fig. 17.13

2. Draw a line GOH making an angle of 35°, the angle of advance, in a direction opposite to the rotation of crank which is clockwise as shown in Fig. 17.13.

3. Draw EOF perpendicular to GOH and mark ON = steam lap = 25 mm and OM = exhaust lap = 8 mm. Through N and M draw lines parallel to GOH which intersect the valve travel circle at C_1, C_2, C_3 and C_4. Now OC_1, OC_2, OC_3 and OC_4 represent the crank positions at admission, cut-off release and compression respectively.

At inner dead centre A and outer dead centre B, the connecting rod is in line with the crank. Since the connecting rod is 4 times the crank radius OA, therefore mark $AA_1 = BB_1 = 4 \times OA = 4 \times 60$ = 240 mm. Now $A_1B_1 = AB$ = 120 mm and represents the stroke of the piston. With C_1, C_2, C_3, C_4 as centres and radius equal to length of connecting rod *i.e.* 240 mm, mark the corresponding positions of piston as shown by points P_1, P_2, P_3 and P_4 in Fig. 17.13. By measurement, the piston position as percentage of stroke is given by :

$$\text{At admission} \quad = \frac{B_1P_1}{B_1A_1} \times 100 \text{ of return stroke} \quad = \frac{119}{120} \times 100 = 99.17\% \quad \textbf{Ans.}$$

$$\text{At cut-off} \quad = \frac{A_1P_2}{A_1B_1} \times 100 \text{ of forward stroke} \quad = \frac{96}{120} \times 100 = 80\% \quad \textbf{Ans.}$$

$$\text{At release} \quad = \frac{A_1P_3}{A_1B_1} \times 100 \text{ of forward stroke} \quad = \frac{116}{120} \times 100 = 96.67\% \quad \textbf{Ans.}$$

$$\text{At compression} \quad = \frac{B_1P_4}{B_1A_1} \times 100 \text{ of return stroke} \quad = \frac{100}{120} \times 100 = 83.33\% \quad \textbf{Ans.}$$

Note : The points p_1, p_2, p_3 and p_4 on AB are the corresponding points of P_1, P_2, P_3 and P_4 respectively. These points may be obtained by drawing the arcs through C_1, C_2, C_3 and C_4 with their centres at P_1, P_2, P_3 and P_4 and radius equal to the length of connecting rod. Now the piston positions as percentage of stroke is given by :

$$\text{At admission} = \frac{Bp_1}{BA} \times 100 \text{ of return stroke ; At cut-off} = \frac{Ap_2}{AB} \times 100 \text{ of forward stroke}$$

$$\text{At release} = \frac{Ap_3}{AB} \times 100 \text{ of forward stroke ; At compression} = \frac{Bp_4}{BA} \times 100 \text{ of return stroke}$$

Positions of the piston as a percentage of the stroke for admission, cut-off, release and compression for crank end of the piston.

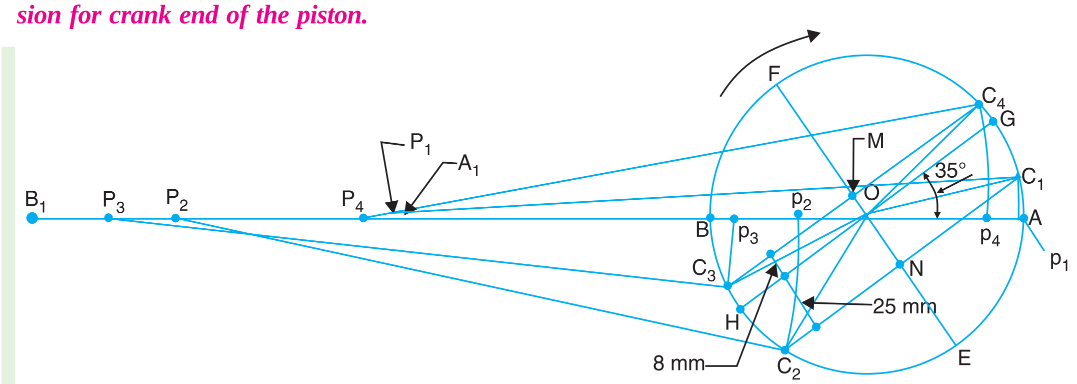


Fig. 17.14

The valve diagram for the crank end is drawn by rotating the valve diagram for the cover end through 180° in the direction of rotation of the crank, as shown in Fig. 17.14. By measurement, the piston positions as percentrage of stroke is given by :

$$\text{At admission} \quad = \frac{B_1P_1}{B_1A_1} \times 100 \text{ of forward stroke} = \frac{Bp_1}{BA} \times 100 \text{ of forward stroke}$$

$$= \frac{119}{120} \times 100 = 99.17\% \quad \textbf{Ans.}$$

At cut-off $= \frac{A_1P_2}{A_1B_1} \times 100$ of return stroke $= \frac{Ap_2}{AB} \times 100$ of return stroke

$= \frac{85}{120} \times 100 = 70.83\%$ **Ans.**

At release $= \frac{A_1P_3}{A_1B_1} \times 100$ of return stroke $= \frac{Ap_3}{AB} \times 100$ of return stroke

$= \frac{112}{120} \times 100 = 93.33\%$ **Ans.**

At compression $= \frac{B_1P_4}{B_1A_1} \times 100$ of forward stroke $= \frac{Bp_4}{BA} \times 100$ of forward stroke

$= \frac{106}{120} \times 100 = 88.33\%$ **Ans.**

Example 17.4. *A slide valve has a travel of 125 mm. The angle of advance of the eccentric is 35°. The cut-off and release takes place at 75 per cent and 95 per cent of the stroke at each end of the cylinder. If the connecting rod is 4 times the crank length, find steam lap, exhaust lap and lead for each end of the valve.*

Solution. Given : $AB = 125$ mm ; $\alpha = 35°$

Piston position at cut-off for both ends (*i.e.* cover and crank end)

= 75% of stroke

Piston position at release for both ends

= 95% of stroke

Steam lap, exhaust lap and lead for the cover end

The Reuleaux's diagram for the cover end, as shown in Fig. 17.15, is drawn as discussed below :

1. First of all, draw $AB = 125$ mm to some suitable scale, to represent the valve travel. This diameter AB also represents the piston stroke. On this diameter AB draw a valve travel circle such that $OA = OB =$ Throw of eccentric. The radius OA or OB also represents the crank radius.

2. Draw a line GOH making an angle of 35°, the angle of advance, in a direction opposite to the rotation of the crank which is clockwise as shown in Fig. 17.15.

3. At inner dead centre A and outer dead centre B, the connecting rod is in line with the crank. Since the connecting rod is 4 times the crank radius, therefore mark $AA_1 = 4 \times OA = 4 \times 125/2 = 250$ mm. Now $A_1B_1 = AB = 125$ mm and represents the stroke of the piston.

Broaching machine. Broaching is a process of machining through holes of any cross sectional shape, straight and helical slots, external surfaces of various shapes, external and internal toothed gears, splines, keyways and rifling.

Note : This picture is given as additional information and is not a direct example of the current chapter.

4. Since the cut-off takes place at 75 percent of the stroke, therefore

$$\frac{A_1P_2}{A_1B_1} = \frac{Ap_2}{AB} = 0.75$$

$\therefore$ $A_1P_2 = A\ p_2 = 0.75 \times A_1B_1 = 0.75 \times 125 = 94$ mm

...($\because A_1B_1 = AB = 125$ mm)

With P_2 as centre and radius equal to $P_2\,p_2$ (*i.e.* length of connecting rod), draw an arc through p_2 which intersects the valve travel circle at C_2. This point C_2 represents the crank-pin position at cut-off.

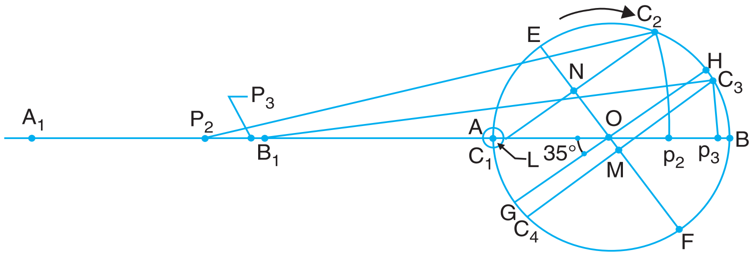


Fig. 17.15

5. From C_2 draw C_2C_1 parallel to *GH* which intersects a line *EOF* (perpendicular to *GOH*) at *N*. The point C_1 represents the crank-pin position at admission and *ON* is the steam lap. By measurement,

Steam lap $= ON = 32$ mm **Ans.**

6. Since the release takes place at 95 % of the stroke, therefore

$$\frac{A_1P_3}{A_1B_1} = \frac{Ap_3}{AB} = 0.95$$

$\therefore$ $A_1P_3 = Ap_3 = 0.95 \times A_1B_1 = 0.95 \times 125 = 118.8$ mm

With P_3 as centre and radius equal to $P_3\ p_3$ (*i.e.* length of connecting rod), draw an arc through p_3 which intersects the valve travel circle at C_3. This point C_3 represents the crank-pin position at release.

7. From C_3 draw C_3C_4 parallel to *GH* which intersects a line *EOF* at *M*. The point C_4 represents the crank-pin position at compression and *OM* is the exhaust lap. By measurement,

Exhaust lap $= OM = 8$ mm **Ans.**

8. In order to find the lead, draw a circle with centre *A* such that C_1C_2 is tangential to this circle (or draw *AL* perpendicular to C_1C_2). The perpendicular *AL* represents the lead of the valve. By measurement,

Lead $= AL = 6$ mm **Ans.**

Steam lap, exhaust lap and lead for the crank end

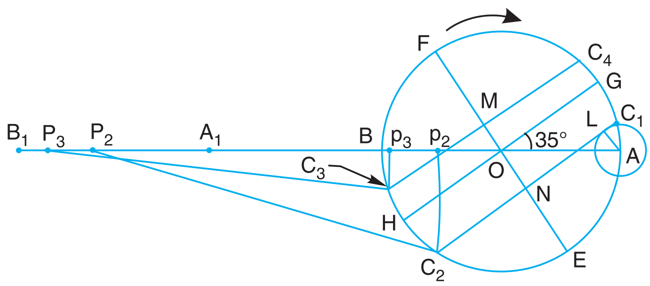


Fig. 17.16

The Reuleaux's valve diagram for the crank end, as shown in Fig. 17.16, is drawn by rotating the valve diagram for the cover end, through 180°. By measurement,

Steam lap $= ON = 20$ mm **Ans.**

Exhaust lap $= OM = 12$ mm **Ans.**

and Lead $= AL = 16$ mm **Ans.**

Example 17.5. *The following data refer to a D-slide valve for the cover end :*

Position of the crank at cut off = 0.7 of stroke ; Lead = 6 mm ; Maximum opening of port to steam = 45 mm ; connecting rod length = 4 times crank length.

Find the travel of valve, angle of advance and steam lap.

Solution. Given : Position of Crank at cut-off = 0.7 of stroke ; Lead = 6 mm ; Maximum opening of port to steam = 45 mm ; Connecting rod length = 4 times the crank length.

The travel of valve, angle of advance and steam lap may be obtained by using Bilgram valve diagram as discussed below :

1. Draw $A'B'$ of any convenient length, as shown in Fig. 17.17, to represent the assumed valve travel. Draw the assumed valve travel circle on this diameter $A'B'$ which also represents the piston stroke (assumed).

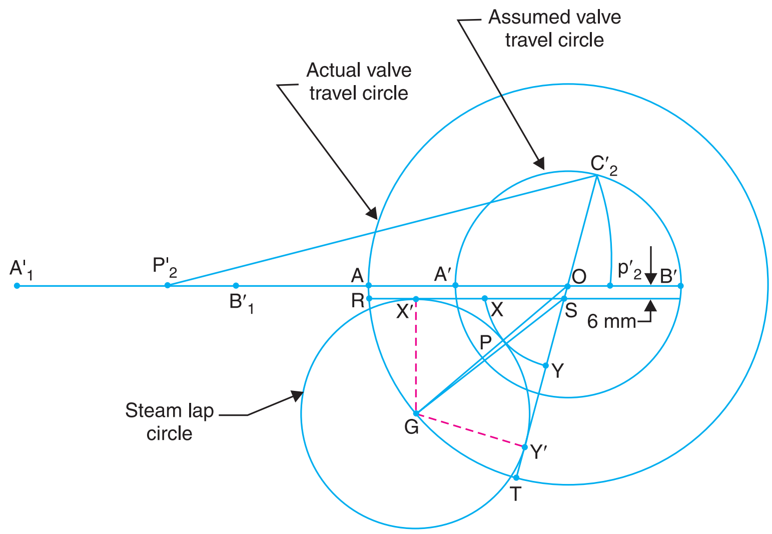


Fig. 17.17

2. Since the length of connecting rod is 4 times the crank OA', therefore mark $A'A'_1 = B'B'_1 = 4 \times OA'$. Now $A'_1 B'_1$ represents the piston stroke.

3. The cut-off for the cover end takes place at 0.7 of the stroke, therefore mark

$$\frac{A_1'P_2'}{A_1'B_1'} = \frac{A'p_2'}{A'B'} = 0.7$$

4. Now P'_2 as centre and radius $P'_2 p'_2$ (*i.e.* length of connecting rod), draw an arc $p'_2 C'_2$. Now OC'_2 represents the crank position at cut-off.

5. Draw a line RS parallel to $A'B'$ and at a distance equal to the lead *i.e.* 6 mm, to some suitable scale. The point S lies on the line $C'_2 OT$.

6. With O as centre, draw an arc of radius equal to the maximum opening of port to steam (*i.e.* 45 mm) which intersects RS at X and OT at Y.

7. Draw the bisector of angle *RST*. The point *G* on this bisector is obtained by hit and trial such that the circle with centre *G* touches the maximum opening arc at *P*, the lines *RS* and *ST*. The point *G* is a point on the actual valve travel circle and represents the centre for steam lap circle.

By measurement, we find that

Travel of valve $= 2\,AO = 2\,GO = 216$ mm **Ans.**

Angle of advance $= \angle AOG = 40°$ **Ans.**

Steam lap $= GP = 63$ mm **Ans.**

Example 17.6. *In a steam engine, the D-slide valve has a cut-off at 70 per cent of the stroke at each end of the cylinder. The steam lap and the lead for the cover end are 20 mm and 6 mm respectively. If the length of the connecting rod is 4 times the crank length, find : valve travel, and angle of advance of the eccentric. Determine also the steam lap and lead of the crank end.*

Solution. Given : Position of piston at cut-off on both sides of the cylinder = 70% of stroke ; Steam lap = 20 mm ; Lead = 6 mm ; Connecting rod length = 4 × crank length.

Valve travel and angle of advance of the eccentric

Since we have to find the valve travel, therefore the Bilgram valve diagram is used. The position of the crank OC'_2 for cut-off at 70 per cent of stroke is obtained in the similar manner as discussed in the previous example.The Bilgram valve diagram is now completed as follows :

1. Draw *RS* parallel to *A' B'* and at a distance equal to the lead *i.e.* 6 mm, to some suitable scale as shown in Fig. 17.18. The point *S* lies on the line $C'_2\,OT$.

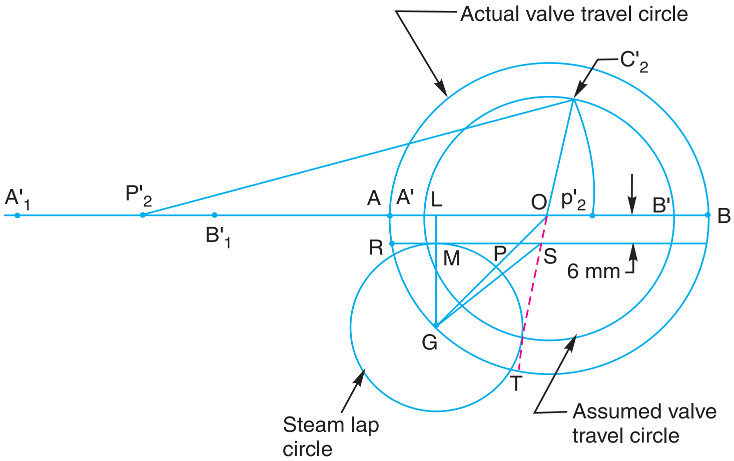


Fig. 17.18

2. Draw the bisector of the angle *RST*. Obtain the *point *G* on this bisector, by hit and trial, such that a circle with centre *G* and radius equal to the steam lap *i.e.* 20 mm touches the lines *RS* and *ST*.

3. Now with *O* as centre and radius equal to *OG* draw the actual valve travel circle.

By measurement, we find that

Valve travel $= AB = 76$ mm **Ans.**

and angle of advance of the eccentric $= \angle AOG = 42°$ **Ans.**

* The point *G* may also be obtained by drawing a perpendicular from *A'O* such that *LG* = steam lap + lead = 20 + 6 = 26 mm.

Steam lap and lead for the crank end

Since the valve travel and angle of advance of the eccentric is known, therefore the steam lap and lead for the crank end may be easily found by using Reuleaux valve diagram as discussed below:

1. Draw AB = 76 mm to some suitable scale, as shown in Fig. 17.19, to represent the valve travel. This diameter AB also represents the piston stroke and $OA = OB$ = Throw of eccentric or radius of crank.

2. Since cut-off for the crank end takes place at 70 per cent of the stroke, threfore mark

$$\frac{Ap_2}{AB} = 0.7 \text{ or } Ap_2 = 0.7 \times AB = 0.7 \times 76 = 53.2 \text{ mm}$$

3. Now with centre P_2 and radius equal to $P_2\,p_2$ (*i.e.* length of connecting rod), draw an arc p_2C_2. Now OC_2 represents the position of crank at cut-off for crank end.

4. Draw GOH at an angle of 42°, the advance of the eccentric, with AB in the direction opposite to the rotation of crank which is shown clockwise in Fig. 17.19.

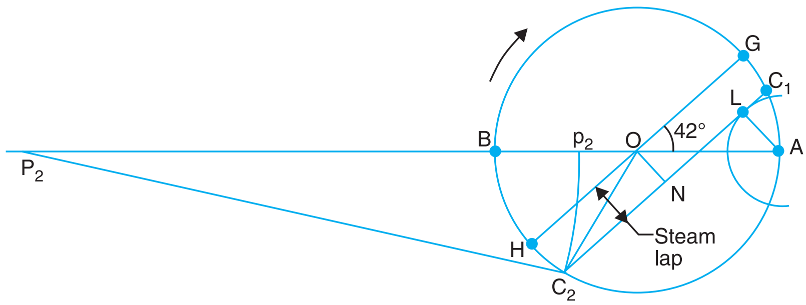


Fig. 17.19

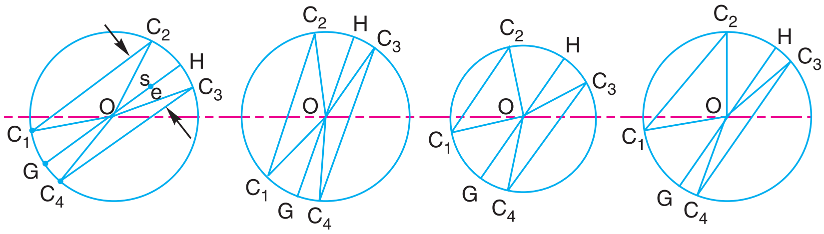
5. From C_2 draw C_2C_1 parallel to GH. Now the perpendicular, ON and AL on C_2C_1 represent the steam lap and lead respectively. By measurement

Steam lap $= ON = 11$ mm **Ans.**

Lead $= AL = 14$ mm **Ans.**

17.11. Effect of the Early Point of Cut-off with a simple Slide Valve

We have seen in the previous articles that the point of cut-off occurs very late *i.e.* when the crank makes an angle greater than 90° with the inner dead centre (or when the piston moves greater than 50 per cent of the stroke), as shown in Fig. 17.20 (*a*). We shall now consider the effect of the early point of cut-off on the points of admission, release and compression. The early point of cut-off (considering the crank at 90°) may be obtained by the following three methods :



(*a*) (*b*) (*c*) (*d*)

Fig. 17.20. Effect of early point of cut-off with a simple slide valve.

First Method

The simplest method of obtaining the earlier cut-off is by increasing the angle of advance of the eccentric while the throw of the eccentric, steam lap and exhaust lap are kept constant. We see from Fig. 17.20 (*b*), that by increasing the angle of advance for the earlier cut-off will also make admission, release and compression earlier than as shown in Fig. 17.20 (*a*). This will, obviously reduce the length of effective stroke of the piston.

Second Method

Fig. 17.20 (*c*) shows that the earlier cut-off may also be obtained by increasing the angle of advance of the eccentric but reducing the throw of the eccentric (or the valve travel) in order to retain the same timing for admission as in the normal diagram shown in Fig. 17.20 (*a*). The steam lap and exhaust lap are constant. We see from Fig. 17.20 (*c*) that the release and compression occur earlier but not so early as in Fig. 17.20 (*b*). The objection to this method is that the maximum opening of the port to steam and exhaust is reduced due to the shortening of valve travel. This will cause withdrawing or throttling of steam.

Blades of the helicopter propeller push the air downwards and the resultant reaction gives helicopter the necessary lifting power.

Note : This picture is given as additional information and is not a direct example of the current chapter.

Third Method

Another method for obtaining the earlier cut-off is to increase the steam lap and the angle of advance of the eccentric, as shown in Fig. 17.20 (*d*), but keeping constant the travel and lead of the valve [*i.e.* same as in Fig. 17.20 (*a*)]. The advantage of this method is that there will be a normal timing of the admission and a smaller reduction in the maximum opening of the port to steam. But the necessity of increasing the steam lap of the valve makes it unsuitable from practical point of view.

17.12. Meyer's Expansion Valve

We have seen in the previous article that in order to obtain earlier cut-off, other operations such as admission, release and compression also take place earlier which is undesirable. The Meyer's expansion valve not only enables the cut-off to take place early in the stroke with normal timing for admission, release and compression, but it also enables the cut-off to be varied while the engine is running. There are two valves known as ***main valve*** and ***expansion valve*** which are driven by separate eccentric from the main crankshaft as shown in Fig. 17.21.

The main valve, is similar to the ordinary slide valve, except that it is provided with extensions and the steam passes from the steam chest through the ports P_1 or P_2. The admission of steam to the main valve is controlled by the expansion valve which slides on the back of the main valve. The expansion valve consists of two blocks or plates E_1 and E_2 mounted on a spindle. It may be noted that in order to admit steam into the cylinder, not only the ports P_1 or P_2 in the main valve are in communication with the main ports P'_1 or P'_2 but at the same time these must be uncovered by the expansion plates E_1 or E_2 as the case may be.

In order to obtain variable cut-off according to the requirement, the position of the plates E_1 and E_2 is varied by means of a spindle having right and left hand threads. The spindle extends to the engine room so that the operator can vary the position of E_1 and E_2 while the engine is running . Thus the variable cut-off is achieved by the expansion valve without the change of lead, maximum opening to steam or points of admission, release and compression.

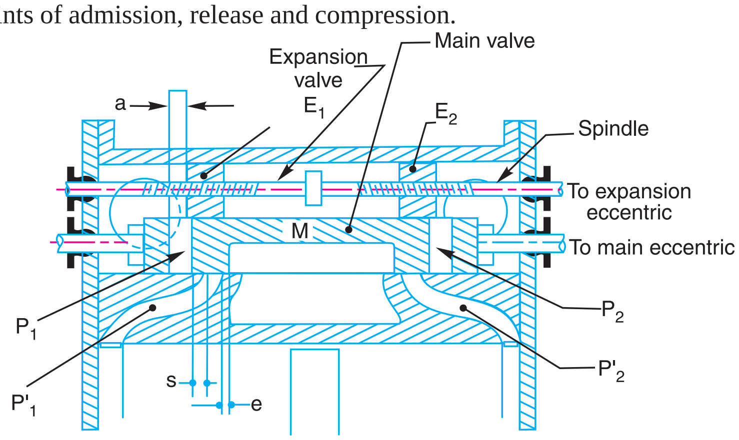


Fig. 17.21. Meyer's expansion valve.

Fig. 17.21 shows that both the valves are in mid-position. A little consideration will show that steam lap (s) and exhaust lap (e) for the main valve are positive whereas the steam lap (a) for the expansion valve is negative (*i.e.* the port P_1 instead of being covered by the expansion valve in mid-position, is open to steam by a distance a). The points of admission, release, compression and the least point of cut-off may be obtained in the usual manner by the Reuleaux or Bilgram valve diagrams.

17.13. Virtual or Equivalent Eccentric for the Meyer's Expansion Valve

In order to obtain the setting of the expansion valve for the predetermined cut-off or ***vice-versa,*** the Reuleaux or Bilgram valve diagram is drawn from the ***virtual*** or ***equivalent eccentric.*** It is defined as an eccentric having such a length and angle of advance that will cause cut-off to take place at the same position, as is caused by the combined effect of main eccentric and expansion eccentric.

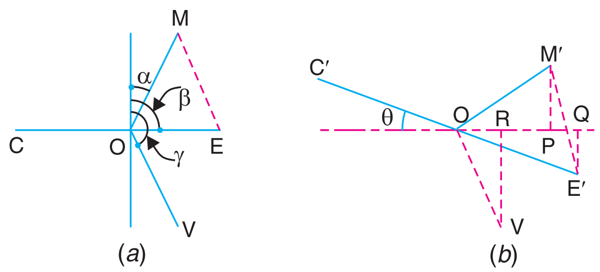
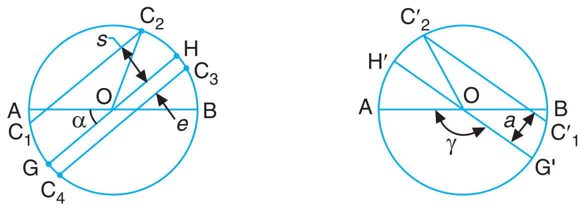


Fig. 17.22. Virtual or equivalent eccentric for the Meyer's expansion valve.

In the Meyer's expansion valve, the main valve is driven by an eccentric having an angle of advance of 25° to 30° and the expansion valve is driven by an eccentric having an angle of advance 80° to 90°. If the engine has to be reversible, the angle of advance must be 90° so that the cut-off takes place at the same fraction of the stroke for the same setting of the expansion valve whatever may be the direction of rotation of the crank. Fig. 17.22 (a) shows the relative positions of the crank OC, main eccentric OM, and expansion eccentric OE, when the crank is at the inner dead centre. The angle of advance of the main eccentric OM is denoted by α and the angle of advance of the expansion eccentric OE is taken as $\beta = 90°$. When the crank OC has tuned through an angle θ from the inner dead centre, the corresponding positions of the main eccentric and the expansion eccentric are shown in Fig. 17.22 (b). The displacement of the main valve from its mid-position is represented by OP, the projection of OM' on the line of stroke. Similarly the displacement of expansion valve from its mid-position is represented by *OQ*, the projection of *OE'* on the line of stroke. In both the cases, the obliquity of the eccentric rod is neglected. The difference between *OQ* and *OP* (*i.e. PQ*) is the displacement of the expansion valve relative to the main valve, in this case towards the right. The displacement *PQ* may also be obtained by drawing a line *O V* parallel and equal to *M'E'* and then *OR*, the projection of *O V* on the line of stroke, will be equal to *PQ*. Thus we see that for the given positions of the main eccentric *OM'* and expansion eccentric *OE'*, the displacement *PQ* is equal to the displacement given by a single eccentric *O V*. This eccentric *O V* is termed as ***virual*** or ***equivalent eccentric.*** Since the throw and the angle of advance are referred with respect to inner dead centre , the virtual or equivalent eccentric may be obtained by drawing *O V* parallel and equal to *ME* in Fig. 17.22 (*a*). Now γ is the angle of advance and *O V* is the throw for the virtual or equivalent eccentric. The cut-off will take place for the crank position in which *R* lies at a distance '*a*' to the left of *O*. This position is most easily found by applying the Reuleaux valve diagram to the virtual or equivalent eccentric *O V*.

Fig. 17.23 (*a*) shows the Reuleaux valve diagram for the main eccentric *OM* in order to determine the crank positions for admission, release, compression and for the latest possible cut-off.



(*a*) For main eccentric *OM*. (*b*) For virtual eccentric *O V*.

Fig. 17.23. Reuleaux valve diagram.

The Reuleaux valve diargam for the virtual eccentric *O V* as shown in Fig. 17.23 (*b*) is drawn as follows :

1. First of all, draw a circle on diameter *A B* = 2 *O V*.

2. Draw *G' H'* making an angle α with *A B* in the direction opposite to the rotation of crank.

3. Draw $C'_1C'_2$ parallel to *G' H'* and at a distance equal to the steam lap (*a*) for the expansion valve.

4. Now OC'_2 represents the crank position at which the cut-off takes place. An increase or decrease of the steam lap (*a*) gives respectively a later or earlier cut-off. The steam lap (*a*) is altered by means of a right and a left hand threaded spindle.

17.14. Minimum Width and Best Setting of the Expansion Plate for Meyer's Expansion Valve

The minimum width and best setting of the expansion plate E_1 or E_2 for the Meyer's expansion valve may be obtained as discussed below :

1. Minimum width of the expansion plate E_1 or E_2

Let *OV* = Throw of the virtual eccentric,

a = Steam lap of the expansion valve, and

p = Width of the port P_1 or P_2 in the main valve as shown in Fig. 17.21.

Since the maximum displacement, from the mid-position, of the expansion valve relative to the main valve is equal to the throw of the virtual eccentric *O V*, therefore

Maximum overlap of the expansion valve and the port

$= OV - a$

∴ Minimum width of the expansion plate E_1 or E_2 (Fig. 17.21) required to prevent steam from being re-admitted past the inner edge of the plate

$= OV - a + p$

2. *Best setting of the expansion plate E_1 or E_2*

Due to the obliquity of the connecting rod, the steam lap (a) for the two expansion plates, for the same point of cut-off, must be different.

Let a_1 = Steam lap for the expansion plate E_1 on the cover side, and

a_2 = Steam lap for the expansion plate E_2 on the crank side.

Generally, the difference between the two steam laps, *i.e.* $(a_1 - a_2)$ is different with the change of point of cut-off. In actual practice, when the expansion plates are assembled on the valve spindle, they may be given different laps. But the difference $(a_1 - a_2)$ once fixed will remain constant for all values of the steam lap. Therefore for the best results, it is necessary to use such a value of $(a_1 - a_2)$ which gives as nearly as possible equal cut-off on both strokes over the full range of cut-off required.

Example 17.7. *The following particulars refer to a Meyer's expansion valve :*

Throw of main eccentric = 50 mm ; angle of advance of main eccentric = 30° ; Throw of expansion eccentric = 55 mm ; Angle of advance of expansion eccentric = 90° ; Ratio of connecting rod length to crank length = 5.

Find : 1. Steam laps required on the expansion plates in order to give cut-off at 0.2, 0.3, 0.4, 0.5, and 0.6 of the stroke on both strokes, 2. The best setting of the expansion plates, and 3. The minimum width of the plate, if the width of the steam port in main valve is 28 mm.

Solution. Given : OM = 50 mm ; α = 30° ; OE = 55 mm ; β = 90° ; Ratio of connecting rod length to crank length = 5

1. ***Steam lap required on the expansion plates***

First of all, determine the throw and angle of advance of the virtual eccentric OV as shown in Fig. 17.24. By measurement, throw of virtual eccentric,

$$OV = 53 \text{ mm}$$

and angle of advance, $\gamma = 143°$

Now draw the Reuleaux valve diagram, as shown in Fig. 17.25, for the virtual eccentric OV as discussed below :

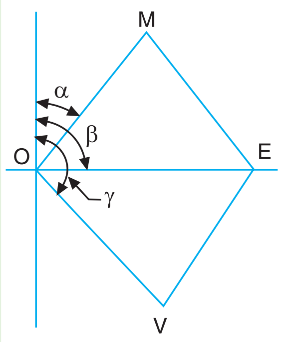


Fig. 17.24

1. Draw a cirlce on the diameter AB, such that

$$AB = 2 \times OV = 2 \times 53 = 106 \text{ mm}$$

2. Draw $C'_1\, OC'_2$ making an angle $\gamma = 143°$ with AB, where γ is the angle of advance for the virtual eccentric.

3. Since the length of connecting rod is 5 times the crank length, therefore draw $AA_1 = BB_1 = 5 \times OA$. The distance $A_1B_1 = AB$ represents the stroke length.

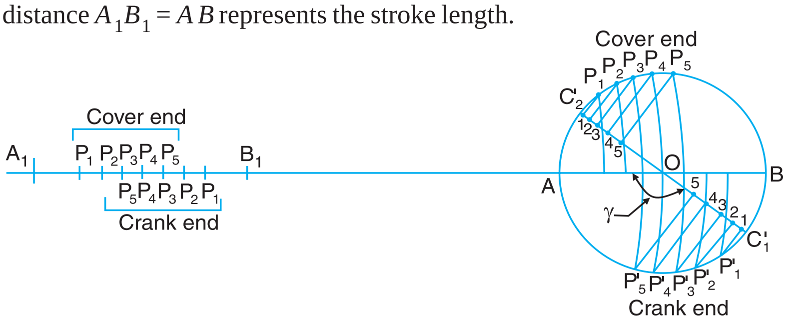


Fig. 17.25

4. Mark the points P_1, P_2, P_3, P_4 and P_5 corresponding to 0.2, 0.3, 0.4, 0.5 and 0.6 of the stroke respectively for the cover end and crank end as shown in Fig. 17.25.

5. Now with centres P_1, P_2, P_3, P_4 and P_5 and radius equal to 5 times OA, obtain the crank-pin positions P'_1, P'_2, P'_3, P'_4, and P'_5 corresponding to 0.2, 0.3, 0.4, 0.5 and 0.6 of the stroke at which cut-off is required to take place for both the ends.

6. The perpendicular distances for P'_1, P'_2 ..... etc. on $C'_1\ OC'_2$ for both the ends represent the steam lap (*a*) for the virtual eccentric. By measurement, the required values of the steam lap (*a*) are tabulated below :

Cut off	0.2	0.3	0.4	0.5	0.6
Steam lap (cover end) in mm	12	24	32	39	46 **Ans.**
Steam lap (crank end) in mm	19	30	39	46	50 **Ans.**
Difference in mm	7	6	7	7	4

2. Best setting of the expansion plates

From the above table, we see that if the steam lap on the end is kept 7mm more than the steam lap on the cover end, then the cut off will occur at approximately the same fraction of the stroke for both ends of the cylinder.

Therefore, for best results, the expansion plates may be set with steam lap at the crank end 7mm greater than that at cover end. **Ans.**

3. Minimum width of expansion plate

From the above table, we see that the minimum steam lap on the cover end is 12 mm and on the crank end is 19 mm. Since the width of the steam port in the main valves is 28 mm (*i.e.* p = 28 mm), therefore

Minimum width of the expansion plate on the cover end

$= OV - a + p = 53 - 12 + 28 = 69$ mm **Ans.** ...(Substituting a = 12 mm)

and minimum width of the expansion plate on the crank end

$= OV - a + p = 53 - 19 + 28 = 62$ mm **Ans.** ...(Substituting, a = 19 mm)

17.15. Reversing Gears

The primary function of the reversing gear is to reverse the direction of motion of the crank-shaft in steam engines. It also enables to vary the power developed by the engine by altering the point of cut-off while the engine is running. Following two types of the reversing gears are generally used :

1. Link motions, and **2.** Radial valve gears.

In ***link motions,*** two eccentrics are keyed to the crankshaft, one for forward motion and the other for backward motion. A suitable link mechanism is introduced between the eccentrics and the valve rod so that the valve may receive its motion either wholly from one of the two eccentrics or partly from one and partly from the other. The examples of link motions are Stephenson link motion, Gooch link motion and Allan link motion. The Stephenson link motion is most widely used.

In ***radial valve gears***, a single eccentric or its equivalent is used which serves the same object as two separate eccentrics of link motions. The examples of radial valve gears are Hackworth gear and Walschaert gear.

Notes : 1. In order to determine the approximate piston position at which admission, cut-off, release and compression takes place for a given setting of the gear, a simplified graphical method may be used. The method consists in finding the throw and angle of advance of a single eccentric (known as virtual or equivalent eccentric) which gives approximately the same motion as obtained from a reversing gear. The method of finding the throw and angle of advance differs for the two types of the reversing gears and is discussed in the following pages.

2. After determining the equivalent eccentric, the Reuleaux or Bilgram valve diagram is drawn to determine the piston positions at which admission, cut-off, release and compression take place for a given setting of the gear.

17.16. Principle of Link Motions–Virtual Eccentric for a Valve With an Offset Line of Stroke

Let *OC* be the crank making an angle θ with the inner dead centre as shown in Fig. 17.26. The corresponding position of one of the eccentrics is represented by *OE* making an angle (θ + α) with the vertical, where α is the angle of advance. As the crank *OC* revolves, the end *A* of the eccentric rod *EA* reciprocates along the line *PA* (*i.e.* in the direction of the path of the valve rod connected to the valve). The line of stroke of the valve is off-set by *OP*. It is required to find the throw and angle of advance of an eccentric with axis at *P*, which will give to *A* the same motion as it receives from the actual eccentric *OE*.

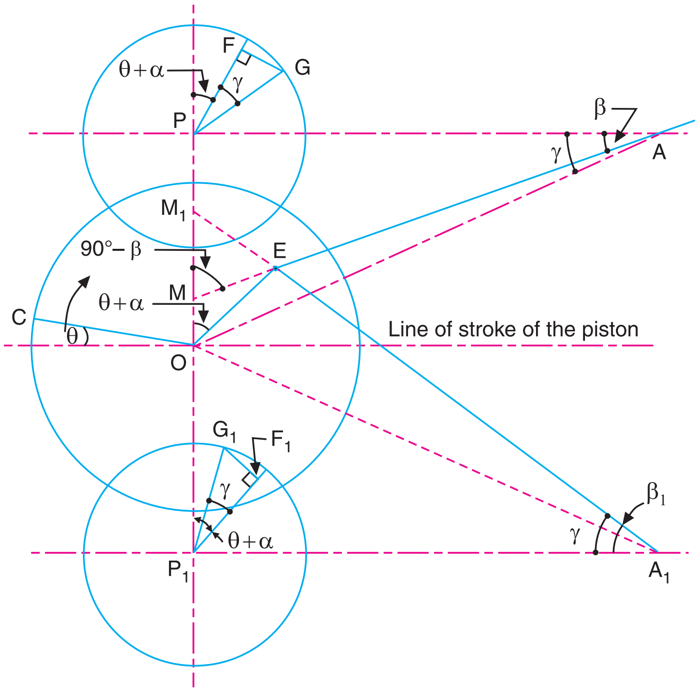


Fig. 17.26. Principle of link motions.

A little consideration will show that when the line *AE* is produced to cut the vertical line *OP* at *M*, then the triangle *OEM* represents the velocity triangle for the mechanism *OEA*, with all its sides perpendicular to those of a usual velocity triangle.

Let ω = Angular speed of crank or eccentric in rad/s,

v_A = Velocity of the point *A*,

v_E = Velocity of the point *E*, and

β = Angle of inclination of *AE* with *AP*.

We know that

$$\frac{v_A}{v_E} = \frac{OM}{OE} = \frac{\sin \angle OEM}{\sin \angle OME} \qquad \ldots \left(\because \text{In any triangle, } \frac{a}{\sin A} = \frac{b}{\sin B} \right)$$

$$= \frac{\sin [180° - (\theta + \alpha) - (90° + \beta)]}{\sin (90° + \beta)} = \frac{\cos (\theta + \alpha + \beta)}{\cos \beta}$$

$$\therefore \quad v_A = v_E \times \frac{\cos (\theta + \alpha + \beta)}{\cos \beta} = \omega \times \frac{OE}{\cos \beta} \times \cos (\theta + \alpha + \beta) \quad ...(\because v_E = \omega . OE)$$

Thus the velocity of A of the eccentric EA is same as can be obtained from a virtual eccentric with centre P having throw equal to (OE/ cos β) and the angle of advance (α + β). Since the position of eccentric OE changes with the rotation of crank , therefore the inclination of the eccentric EA with the horizontal (*i.e.* angle β) also changes. This change of angle β is very small because the eccentric rod length EA is 10 to 20 times the throw of eccentric OE. If γ is taken as the mean inclination of the eccentric rod EA, then the throw of virtual eccentric will be OE/ cos γ with an angle of advance (α + γ). Such an arrangement of the eccentric rod is called ***open rod arrangement.***

If the eccentric rod EA instead of lying above the line of stroke of the piston (*i.e.* open rod arrangement), it is in crossed position by crossing the line of stroke (*i.e.* crossed-rod arrangement) as shown by EA_1 in Fig. 17.26, then the velocity triangle for the mechanism OEA_1 will be triangle OEM_1. In this case

$$\frac{v_{A1}}{v_E} = \frac{OM_1}{OE} = \frac{\sin \angle OEM_1}{\sin \angle OME}$$

$$= \frac{\sin [180° - (\theta + \alpha) - (90° - \beta_1)]}{\sin (90° - \beta_1)} = \frac{\cos (\theta + \alpha - \beta_1)}{\cos \beta_1}$$

$$\therefore \quad v_{A1} = v_E \times \frac{\cos (\theta + \alpha - \beta_1)}{\cos \beta_1} = \omega \times \frac{OE}{\cos \beta_1} \times \cos (\theta + \alpha - \beta_1)$$

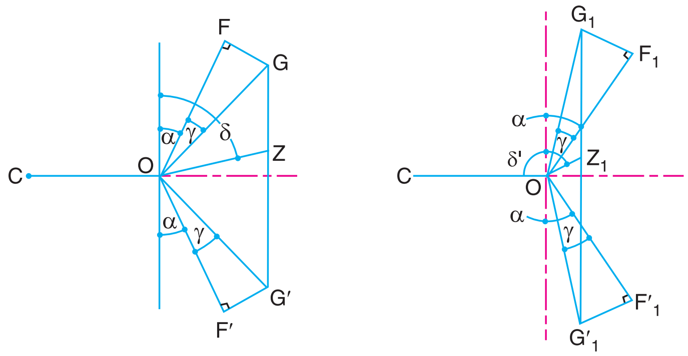
$$= \omega \times \frac{OE}{\cos \gamma} \times \cos (\theta + \alpha - \gamma) \quad ...(\text{Taking mean } \beta_1 = \gamma)$$

From the above expression, we see that for the crossed rod arrangement, the throw for the virtual eccentric with centre P_1 is same *i.e.* OE/ cos γ but the angle of advance is (α – γ).

The throw and angle of advance of the virtual eccentric may be determined by the simple graphical construction as discussed below :

1. For A, draw PF parallel and equal to OE. From F draw FG perpendicular to PF. The angle FPG is equal to γ. Now PG is the virtual eccentric.

2. Similarly for A_1, P_1G_1 is the virtual eccentric.



(*a*) For open rod arrangement (*b*) For crossed rod arrangement.

Fig. 17.27. Determination of virtual eccentrics.

We have already discussed that in link motions, there are two eccentrics. These two eccentrics are connected to their respective eccentric rods. The ends of these eccentric rods are connected to a slotted link in which a die block slides. The die block is connected to the valve through a valve rod. The resultant graphical construction for the open rod and crossed rod arrangements is shown in Fig. 17.27 (*a*) and (*b*) respectively. The determination of virtual eccentrics *OG* and *OG'* for the two eccentrics of the open rod arrangement is shown in Fig. 17.27 (*a*) whereas the determination of virtual eccentrics OG_1 and OG'_1 for the eccentrics of the crossed rod arrangement is shown in Fig. 17.27 (*b*). The straight lines *GG'* in Fig. 17.27 (*a*) and $G_1G'_1$ in Fig. 17.27 (*b*) are divided at *Z* and *Z'* respectively in the same ratio in which the die block, for a given setting of the link motion, divides the slotted link in which it slides. Now *OZ* is the throw of the virtual eccentric and δ is the angle of advance for the open rod arrangement. Similarly OZ_1 is the throw of the virtual eccentric and δ' is the angle of advance for the crossed rod arrangement.

17.17. Stephenson Link Motion

The Stephenson link motion, as shown in Fig. 17.28, is the most commonly used reversing gear in steam engines. It is simple in construction and gives a good steam distribution. Fig. 17.28 shows the arrangement of the gear in mid-position, where *OC* is the crank and *OE* and OE_1 are the two eccentrics fixed on the driving shaft or axle in case of a locomotive. The eccentric *OE* is for

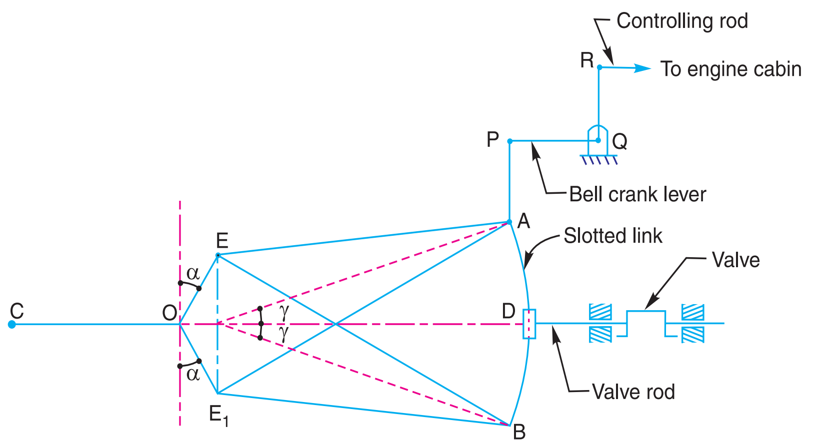


Fig. 17.28. Stephenson link motion.

forward running and OE_1 is for backward running. The motion of these eccentrics is transmitted to the *curved slotted link *AB* by means of eccentric rods *EA* and E_1B respectively. The link *AB* can also slide on the die block *D*. The end *A* on the slotted link is connected to the controlling rod in the engine cabin through the link *AP* and the bell crank lever *RQP* which is pivoted at the fixed fulcrum *Q*. By moving the lever, the curved link *AB* is made to slide through the block *D* and enables the latter to derive its motion either from *B* or *A*. In this way, the point of cut-off may be changed and the direction of motion of the engine may be reversed. The valve receives its motion from the block *D* and the valve rod is guided horizontally.

It may be noted that when the eccentrics *OE* and OE_1 drives the eccentric rods *EA* and E_1B respectively, then the link motion is said to have an open rod arrangement. On the other hand, if the eccentrics *OE* and OE_1 drives the eccentric rods *EB* and E_1A respectively, then the link motion is said to have crossed rod arrangement. This arrangement gives different steam distribution.

* The radius of curvature of the link *AB* with either open or crossed rod arrangement is generally equal to the length of the eccentric rod *EA* or E_1B.

The link motion is said to be in ***full forward gear position,*** when the curved link is lowered so that *A* and *D* coincides. In this position, the valve receives its motion entirely from the eccentric *OE*. When the curved link is raised so that *B* and *D* coincide, it is said to be in ***full backward gear position.*** In this position, the valve recieves its motion entirely from the eccentric OE_1. Similarly, when *D* lies in the middle of *A B*, the link motion is said to be in ***mid-gear position.*** In this position (or for any other position of *D* between *A B*), the valve recieves its motion partly from the eccentric *OE* and partly from the eccentric OE_1.

17.18. Virtual or Equivalent Eccentric for Stephenson Link Motion

The Stephenson link motion in an intermediate position is shown in Fig. 17.29. Let us now find out the equivalent eccentric for the intermediate positions of the die block *D*. If we assume that ends *A* and *B* of the curved link *A B* move along a straight path parallel to the line of stroke of the valve, the equivalent eccentric for the ends *A* and *B* and for the die block *D* may be determined in the similar manner as discussed in Art 17.16. Fig. 17.30 (*a*) and (*b*) has been reproduced for the two positions (*i.e.* when *D* is in mid-position and in intermediate position) of the open rod arrangement. In Fig. 17.30 (*a*), *OH* is the equivalent eccentric for the mid-gear whereas in Fig. 17.30 (*b*), *OZ* is the equivalent eccentric for any other position. If the construction is repeated for different positions of the die block *D*, various points similar to *Z* may be obtained. Now a curve is drawn through the various positions of *Z*. A close approximation to this curve may be obtained by drawing a circular arc through the points *E*, *H* and E_1 as shown in Fig. 17.30 (*a*). Now the equivalent eccentric for the gear position, as shown in Fig. 17.29, may be determined by dividing the *arc EHE_1 at *Z* in the same ratio as *D* divides *A B*.

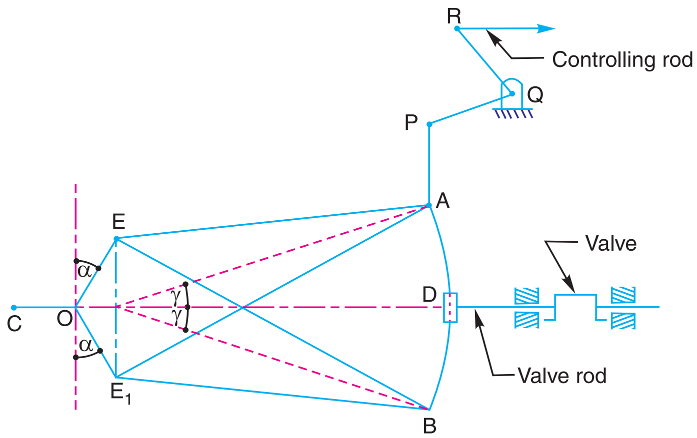


Fig. 17.29. Stephenon link motion in an intermediate position.

Let *R* be the radius of the arc of the circle representing the locus of the points similar to *Z* as shown in Fig. 17.30 (*a*).

$$\therefore \quad R^2 = (OJ)^2 + (EJ)^2 = (OH - HJ)^2 + (EJ)^2 = (R - HJ)^2 + (EJ)^2$$

$$= R^2 + (HJ)^2 - 2R \times HJ + (EJ)^2$$

or

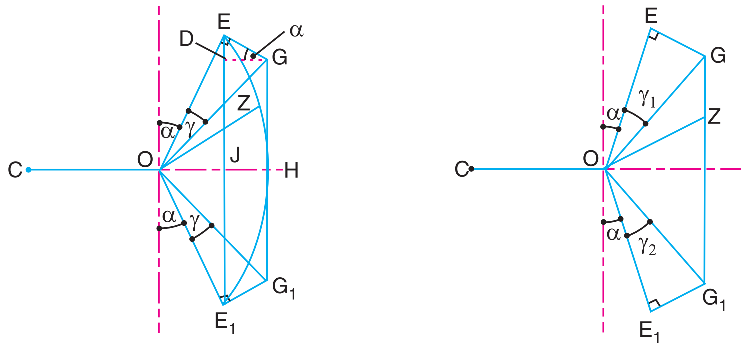
$$R = \frac{(HJ)^2 + (EJ)^2}{2\,HJ} \qquad \text{...}(i)$$

Now

$$EJ = OE \cos \alpha \qquad \text{...}(ii)$$

* A very close result can be obtained by dividing *GH* at *Z* in the same ratio as *D* divides *A B*.

and $\qquad HJ = GD = EG \cos\alpha = (OE \tan\gamma) \cos\alpha$ ...(*iii*)



(*a*) (*b*)

Fig. 17.30. Equivalent eccentric for the two positions of the open rod arrangement.

Substuting the values of *EJ* and *HJ* from equations (*ii*) and (*iii*) in equation (*i*),

$$R = \frac{(OE \tan\gamma)^2 \cos^2\alpha + (OE \cos\alpha)^2}{2(OE \tan\gamma)\cos\alpha}$$

$$= \frac{OE \cos\alpha\,(1+\tan^2\gamma)}{2\tan\gamma} = \frac{OE \cos\alpha \times \sec^2\gamma}{2\tan\gamma} \qquad ...(\because 1+\tan^2\gamma = \sec^2\gamma)$$

$$= \frac{OE \cos\alpha}{2\sin\gamma\cos\gamma} = \frac{OE\cos\alpha}{\sin 2\gamma} \qquad ...(iv)$$

where γ = Mean inclination of the eccentric rod to the line of stroke of the valve.

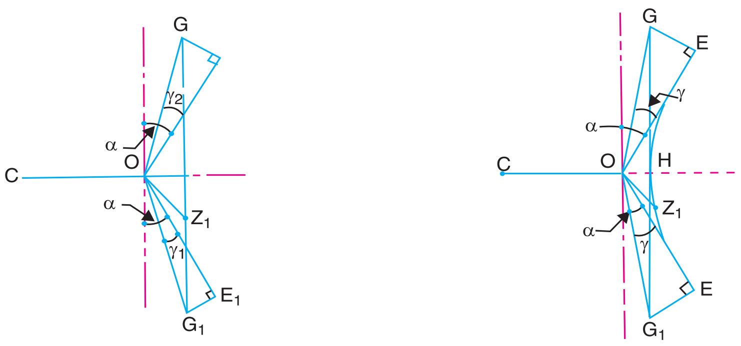
Since γ is very small, therefore $\sin 2\gamma = 2\gamma$ in radians. From Fig. 17.29,

$$\sin 2\gamma = 2\gamma = \frac{\text{arc } AB}{OA} = \frac{\text{arc } AB}{AE}$$

Now equation (*iv*) may be written as

$$R = OE \cos\alpha \times \frac{EA}{\text{arc } AB} \qquad ...(v)$$

The equivalent eccentric for the two positions of the crossed rod arrangement, as shown in Fig. 17.31 (*a*) and (*b*), may be determined in the similar manner as discussed above.



(*a*) (*b*)

Fig. 17.31. Equivalent eccentric for the two positions of the crossed rod arrangement.

After finding the equivalent eccentric for a given setting of the gear, the corresponding Reuleaux of Bilgram diagram is drawn to determine the crank positions at admission, cut-off, release and compression.

Note: Comparing Fig. 17.30 (*a*) for open rod arrangement and Fig. 17.31 (*a*) for crossed rod arrangement, we see that the projection of the virtual eccentric on the line of stroke for any given setting of the gear when it moves from full gear to mid gear position,

1. increases in case of open rod arrangement, and

2. decreases in case of crossed rod arrangement.

This projection is equal to steam lap plus lead. The steam lap being constant, it follows that during *linking up* the gear (*i.e.* when the gear moves from full gear position to mid-gear position), the lead increases in open rod arrangement, while it decreases in crossed rod arrangement.

Example 17.8. *A stephenson link motion with open rods has a throw of each eccentric 75 mm and an angle of advance 18º. The length of the curved slotted link is 400 mm and its radius of curvature is equal to the length of the eccentric rod which is 1.15 m. Determine the throw and angle of advance of the equivalent eccentric when* **1.** *the gear is in the mid-position and* **2.** *the gear is in the middle of full-gear and mid-gear.*

Solution. Given OE = 75 mm ; α = 18º; Arc AB = 400 mm; EA = 1.15 m = 1150 mm

1. Throw and angle of advance of the equivalent eccentric when the gear is in mid-position

Let R = Radius of the arc or the locus of points similar to Z, as shown in Fig. 17.30 (*a*).

We know that

$$R = OE \cos \alpha \times \frac{EA}{\text{arc } AB}$$

$$= 75 \times \cos 18^\circ \times \frac{1150}{400} = 205 \text{ mm}$$

Now draw OE and OE_1 equal to 75 mm and at an angle of 18º to vertical $Y\,Y_1$ as shown in Fig. 17.32. The point P on the line of stroke is found by drawing an arc either from E or E_1 such that $EP = E_1P = R$ = 205 mm. With P as centre and radius 205 mm draw an arc EHE_1. Now OH represents the equivalent eccentric and angle YOH is its angle of advance when the gear is in mid-position. By measurement, throw of equivalent eccentric,

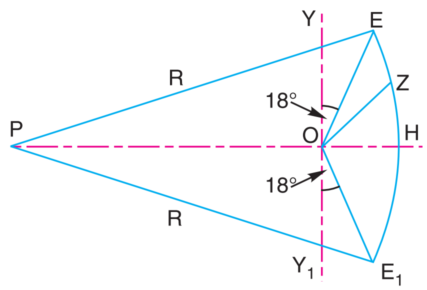


Fig. 17.32

OH = 38 mm **Ans.**

and angle of advance = $\angle YOH = 90$ **Ans.**

2. Throw and angle of advance of the equivalent eccentric when the gear is in the middle of the full-gear and mid-gear

In Fig. 17.32, the point E represents the full-gear position and H the mid-gear position. When the gear is in the middle of the full-gear and mid-gear positions, *i.e.* in the middle of E and H, divide the arc EH such that $EZ = ZH$. Now OZ represents the equivalent eccentric and angle YOZ is its angle of advance. By measurement, throw of equivalent eccentric,

OZ = 50 mm **Ans.**

and angle of advance = $\angle YOH$ = 45º **Ans.**

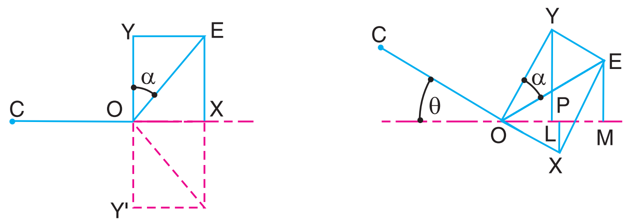
17.19. Radial Valve Gears

We have already discussed that in radial valve gears, only one eccentric or its equivalent is used. The principle on which the radial valve gears operate is discussed below :

Let *OC* be the crank and *OE* the eccentric for a *D*-slide valve as shown in Fig. 17.33 (*a*). *OX* and *OY* are the projections of *OE* along *OC* and perpendicular to *OC* respectively. When the crank turns through an angle θ from the inner dead centre, the distance moved by the valve from its mid-position is given by *OM* which is the projection of the eccentric *OE* on the line of stroke, as shown in Fig. 17.33 (*b*). *OX* and *OY* are the projections of the eccentric *OE* along the crank *OC* and perpendicular to *OC*. *OP* and *OL* are the projections of *OX* and *OY* on the line of stroke. From Fig. 17.33 (*b*),

$$OM = OL + LM = OL + {}^{*}OP$$

From the above expression, it follows that a motion given to the valve by the eccentric *OE* (*i.e.* displacement *OM*) may be obtained by combining the displacements *OL* and *OP* obtained from two separate eccentrics *OY* and *OX*. The eccentric *OY* is 90º out of phase with the engine crank *OC* and is known as ***90º component eccentric.*** The eccentric *OX* is 180º out of phase with the engine crank *OC* and is known as ***180º component eccentric.***



(*a*) (*b*)

Fig. 17.33. Radial valve gear.

The critical examination of Fig. 17.33 shows that

1. The throw of the 180º component eccentric (*i.e.* *OX*) is equal to the sum of steam lap and lead. If lead is kept constant for all settings of the gear, the throw of the 180º component eccentric will also be constant.

2. If the throw of the 90º component eccentric (*i.e.* *OY*) is reduced, the eccentric *OE* will have larger angle of advance α (∵ $\tan \alpha = OX/OY$). The increase of angle of advance will cause cut-off to take place earlier in the stroke of the piston.

3. In order to reverse the direction of rotation of the crank, the direction of 90º component eccentric must be reversed as shown by *OY'* in Fig. 17.33 (*a*).

17.20. Hackworth Valve Gear

This is the earliest of the radial valve gears in which the eccentric *OE* is placed directly opposite to the main crank *OC*, as shown in Fig. 17.34. The eccentric centre *E* is coupled to a sliding or die block *D* which reciprocates along the slotted bar *GH* which is pivoted to the frame at *F*. The slotted bar *GH* is inclined to *OF* which is perpendicular to the line of stroke. The inclination of *GH* (*i.e.* angle β) is fixed for a given setting of the gear and is a maximum for the full gear positions. In order to reverse the direction of rotation of the engine, the slotted bar *GH* is tilted into the dotted position as shown in Fig. 17.34. In mid-gear position,the slotted bar occupies the vertical position *OZ* so that the motion of die block *D* is then perpendicular to the line of stroke of the engine. For constant lead of the valve for all settings, the length of eccentric rod *ED* must be such that *D* and *F* coincide, when the crank is in either dead centre positions. The valve is driven by a connecting link *AB* from a point *A* on the eccentric rod *ED*.

* *LM* = *OP*, being the projection of two equal and parallel lines *OX* and *EY* respectively.

The throw of the virtual or equivalent eccentric and its angle of advance may be determined as follows :

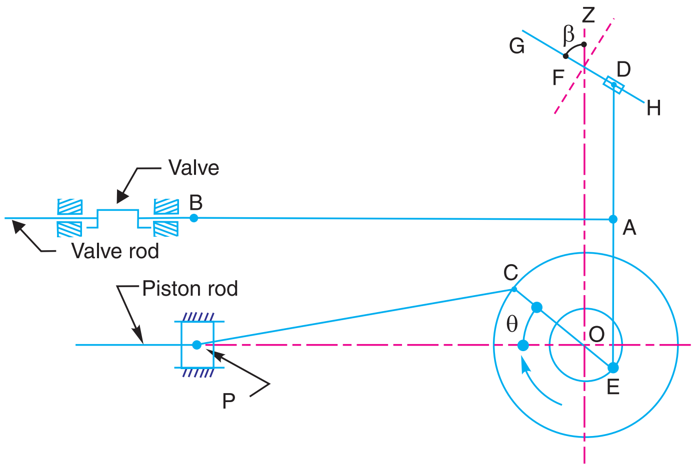


Fig. 17.34. Hackworth valve gear.

The virtual eccentric *OV* is assumed to be equivalent to two eccentrics, *i.e.* 180° component eccentric *OX* and 90° component eccentric *O Y*, as shown in Fig. 17.35 (*a*). First of all, let us find the values of *OX* and *O Y*. During the motion of crank *OC* from one dead centre to another dead centre, the point *E* on the eccentric as well as link *DAE* moves through a distance equal to 2 *OE* along the line of stroke, while the distance moved perpendicular to the line of stroke is zero because *D* occupies the position *F* at both the dead centres. Now the displacement of the valve during the motion of crank from one dead centre to another will be *AA*′ or 2 *OX*. This may be clearly understood from Fig. 17.35 (*b*).

$$\therefore \quad \frac{2OX}{2OE} = \frac{DA}{DE} \quad \text{or} \quad OX = \frac{DA}{DE} \times OE \qquad \ldots (i)$$

This equation shows that the throw of 180° component eccentric is independent of the setting of the gear. This throw (*i.e.* *O X*) is equal to steam lap plus lead.

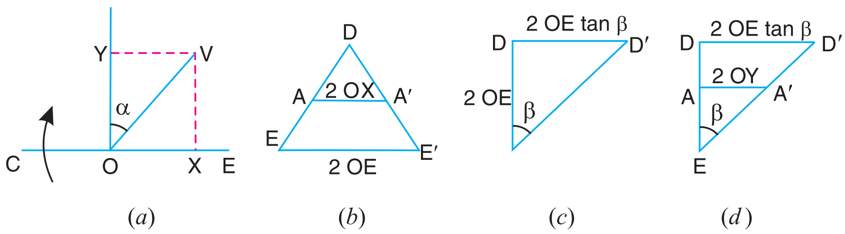


Fig. 17.35. Determination of throw and angle of advance of the virtual or equivalent eccentric.

Now considering the motion of the crank *OC* from one vertical position to another vertical position. The point *E* on the eccentric as well as the link *DAE* moves through a vertical distance equal to 2 *OE*, while the horizontal distance moved by the point *E* is zero. Since the slotted bar *GH* is inclined at an angle β, therefore from Fig. 17.35 (*c*),

Horizontal distance moved by $D = DD' = 2OE \tan \beta$

Now the displacement of the valve during the motion of crank from one vertical position to another will be 2 *O Y*. Therefore from Fig. 17.35 (*d*),

$$\frac{2\,OY}{2\,OE\tan\beta} = \frac{EA}{ED} \quad \text{or} \quad OY = \frac{EA}{ED} \times OE\ \tan\beta \qquad \text{...}(ii)$$

This equation shows that the throw of 90º component eccentric varies with the angle β *i.e.* with the particular setting of the gear.

From Fig. 17.35 (*a*), the throw of the virtual eccentric,

$$OV = \sqrt{(OX)^2 + (OY)^2} \qquad \text{...}(iii)$$

and the angle of advance of the virtual eccentric,

$$\alpha = \tan^{-1}\frac{OX}{OY} \qquad \text{...}(iv)$$

Inside view of a factory.

Note : This picture is given as additional information and is not a direct example of the current chapter.

The equivalent eccentric for a given setting of the gear may be determined graphically as discussed below :

1. Draw *OE*, to some suitable scale, to represent the throw of the actual eccentric as shown in Fig. 17.36.

2. Through *E*, draw *ED* inclined at angle β to *OE* so that *OD* represents *OE* tan β to scale. The angle β is drawn upwards when slotted bar *GH* (Fig. 17.34) is in full line position and it is drawn downwards when *GH* is tilted to the dotted position, as shown in Fig. 17.36.

3. Divide *OE* at *X* in the same proportion as *A* divides *ED* in Fig. 17.34. Through *X* draw a line perpendicualr to *OE* to meet *ED* at *V*. Now *OV* is the equivalent eccentric for the motion of the valve.

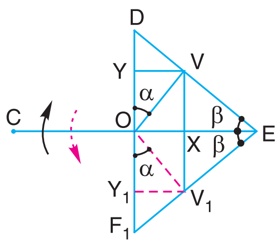


Fig. 17.36

Example 17.9. *In a Hackworth radial valve gear, as shown in Fig. 17.37, the dimensions of various link are as follows :*

OC = 225 mm; CP = 800 mm; DE = 625 mm and AE = 300 mm

If the lead is constant at 3 mm, the steam lap is 18 mm and the angle β is 20º, find the length of eccentric OE, the distance OF, the effective valve travel and the effective angle of advance.

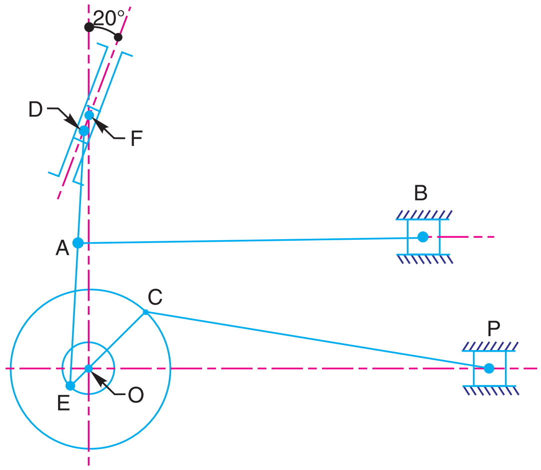


Fig. 17.37

Solution. Given : l = 3 mm ; s = 18 mm ; β = 20º

Length of eccentric OE

We know that in case of a Hackworth radial valve gear, the virtual eccentric *OV* may be assumed to be equivalent to two eccentrics, *i.e.* 180º component eccentric and 90º component eccentric as shown in Fig. 17.38. The throw of the 180º component eccentric is given by

$$OX = \frac{DA}{DE} \times OE = \frac{DE - AE}{DE} \times OE = \frac{625 - 300}{625} \times OE$$

$$= 0.52\ OE \quad \text{...}(i)$$

Also $OX = s + l = 18 + 3 = 21$ mm ...(*ii*)

From equations (*i*) and (*ii*),

$$OE = 21/0.52 = 40.4 \text{ mm}$$

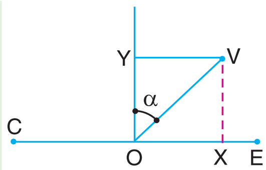


Fig. 17.38

Distance OF

When the eccentric *OE* is along the line of stroke, the point *D* coincides with *F* and the angle *FOE* = 90º.

$$\therefore \quad (OF)^2 + (OE)^2 = (DE)^2$$

or $$OF = \sqrt{(DE)^2 - (OE)^2} = \sqrt{(625)^2 - (40.4)^2} = 623.7 \text{ mm} \quad \textbf{Ans.}$$

Effective valve travel

We know that the 90º component eccentric,

$$OY = \frac{EA}{ED} \times OE \tan\beta = \frac{300}{625} \times 40.4 \tan 20º = 7.06 \text{ mm}$$

∴ Throw of the virtual eccentric,

$$OV = \sqrt{(OX)^2 + (OY)^2} = \sqrt{(21)^2 + (7.06)^2} = 22.15 \text{ mm}$$

and effective valve travel $= 2 \times OV = 2 \times 22.15 = 44.3$ mm **Ans.**

Effective angle of advance

We know that effective angle of advance,

$$\alpha = \tan^{-1}\left(\frac{OX}{OY}\right) = \tan^{-1}\left(\frac{21}{7.06}\right) = \tan^{-1} 2.9745 = 71.4^{\circ} \textbf{ Ans.}$$

17.21. Walschaert's Valve Gear

The Walschaert's valve gear, as shown in Fig. 17.39, is the most extensively used of all reversing gears on modern locomotives. In this gear, a single eccentric *OE* is used and is set at 90° to the main crank *OC*. The eccentric rod *EG* oscillates the curved slotted link *GH* about the fulcrum *F* which is fixed to the frame of the engine. The relative motion of the sliding or die block *D* in the curved slotted link *GH* is due to the link *PQ* which is operated by means of a bell crank lever *SRQ* and a rod from the engine room. The die block *D* is capable of movement along the whole length of the link *GH*. The pin *K* receives its motion from the die block *D* and ultimately from the eccentric *OE*, while the pin *L* receives its motion from a point *B* on the main crosshead *A*, where *AC* is the connecting rod of the engine.

When the gear is in mid-position, the block *D* is at *F*. The radius of link *GH* is such that when the crank *OC* is at the inner dead centre position and the gear is reversed, the point *K* remains at rest. This characteristic gives constant lead during all conditions of running.

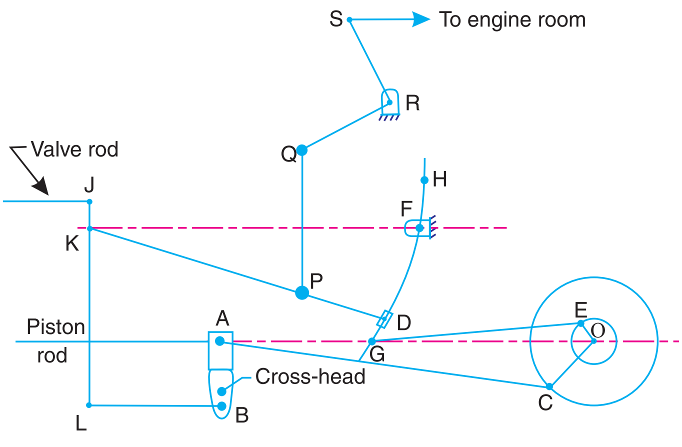


Fig. 17.39. Walschaert's valve gear.

Neglecting obliquities of all the rods, the throw of the virtual eccentric and its angle of advance may be determined in the similar manner as discussed in the previous article. The virtual eccentric *OV* is assumed to be equivalent to two eccentrics *i.e.* 180° component eccentric *OX* and 90° component eccentric *OY*, as shown in Fig. 17.40 (*a*).

First of all, let us find the values of *OX* and *OY*. Considering the motion of crank *OC* from one dead centre to another dead centre, the crosshead *A* and hence the point *L* on the link *JKL* moves through a distance equal to 2 *OC*. During this motion of the crank, the point *G* on the slotted link and hence the point *K* on the link *JKL* occupy the same position as at start. In other words, the distance moved by *K* is zero. Now the displacement of the valve during the motion of crank from one dead centre to another dead centre will be *JJ'* or 2 *OX*.

From Fig. 17.40 (*b*),

$$\frac{2\,OX}{2\,OC} = \frac{JK}{KL} \quad \text{or} \quad OX = \frac{JK}{KL} \times OC \qquad \ldots(i)$$

Thus OX is constant for all positions of the block D on the link GH and the lead remains unchanged during all conditions of running. In case the point J lies on the same side of K as L, the motion of J and L will be in phase. In this position, OX is termed as ***0° component eccentric.***

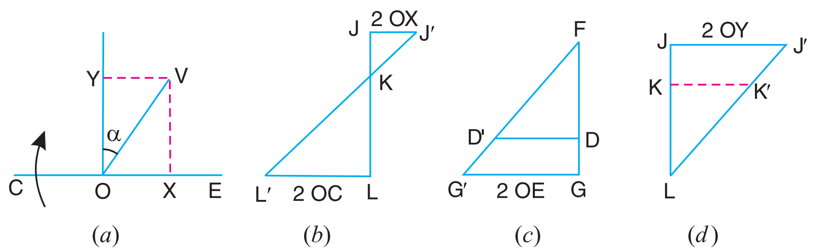


Fig. 17.40. Determination of throw and angle of advance of the virtual eccentric.

Now considering the motion of the eccentric OE from one dead centre position to another dead centre, the crank pin C moves from one vertical position to another, thus not traversing any horizontal distance. During this motion of the eccentric, the distance moved by the crosshead A and thus the point L on the link JKL will be zero. At the same time, the point E on the eccentric OE and the point G on the curved slotted link GH moves through a distance 2 OE. Since the curved slotted link GH is hinged at F, therefore the die block D moves through a distance DD' which is given by

$$\frac{DD'}{2\,OE} = \frac{FD}{FG} \quad \text{or} \quad DD' = \frac{FD}{FG} \times 2\,OE \qquad \text{...[From Fig. 17.40 (c)]}$$

Since point K lies on the link DK, therefore point K will move through the same distance as that of D, *i.e.*

$$KK' = DD' = \frac{FD}{FG} \times 2\,OE$$

Now the displacement of the valve during the motion of the crank from one vertical position to another will be JJ' or 2 OY. From Fig. 17.40 (d),

$$\frac{JJ'}{KK'} = \frac{JL}{KL} \quad \text{or} \quad \frac{2\,OY \times FG}{FD \times 2\,OE} = \frac{JL}{KL}$$

$$\therefore \qquad OY = \frac{JL}{KL} \times \frac{FD}{FG} \times OG \qquad \text{...(ii)}$$

The position of D on the curved slotted link GH may be varied by operating the bell crank lever from the rod in the engine room in order to suit load conditions or to effect the reversal of direction or rotation.

From Fig. 17.40 (a), the throw of the virtual eccentric,

$$OV = \sqrt{(OX)^2 + (OY)^2} \qquad \text{...(iii)}$$

and the angle of advance of the virtual eccentric,

$$\alpha = \tan^{-1} \frac{OX}{OY} \qquad \text{...(iv)}$$

Example 17.10. *In a Walschaert valve gear, as shown in Fig. 17.39, the engine crank is 300 mm long. The least cut-off in the head end of the cylinder is at 120°. At this, the maximum opening to steam is 45 mm and the lead is 6 mm. If the length of the eccentric is 115 mm, find the ratios* $\frac{JL}{KL}$ *and* $\frac{FG}{FD}$ *of the gear. Neglect the obliquities of all the rods.*

Solution. Given : OC = 300 mm ; crank angle at cut-off = 120° ; Maximum opening to steam = 45 mm ; l = 6 mm ; OE = 115 mm

First of all, draw the Bilgram valve diagram as discussed below :

1. Draw OC_2, the position of crank at cut-off, at 120° to the line of stroke *OV* as shown in Fig. 17.41.

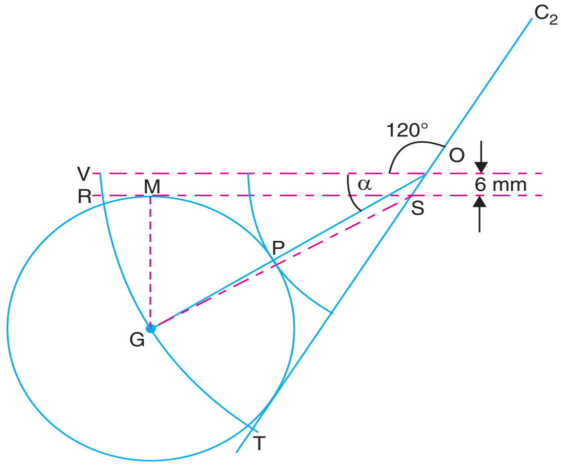


Fig. 17.41

2. Draw a line parallel to *OV* and at a distance equal to the lead (6 mm) which intersects C_2O produced at *S*.

3. With centre *O*, draw an arc with radius *OP* = 45 mm, the maximum opening of steam.

4. Draw the bisector of the angle *RST*. On this bisector, obtain a point *G* such that a circle drawn with centre *G* touches the lines *SR*, *ST* and the point *P*. Join *OG*.

By measurement, we find that throw of the virtual eccentric,

$$OV = OG = 81.5 \text{ mm}$$

and angle of advance of the virtual eccentric

$$\alpha = 32°$$

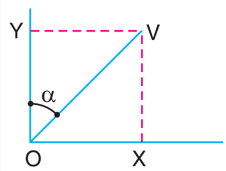


Fig. 17.42

The virtual eccentric *OV* is assumed to be equivalent to two eccentrics, *i.e.* 180° component eccentric *OX* and 90° component eccentric *OY*, as shown in Fig. 17.42.

∴ 180° component eccentric

$$= OX = VY = OV \sin \alpha = 81.5 \sin 32° = 43.2 \text{ mm}$$

and 90° component eccentric,

$$OY = OV \cos 32° = 81.5 \times 0.848 = 69.1 \text{ mm}$$

We know that $OX = \dfrac{JK}{KL} \times OC$ ...(Refer Fig. 17.39)

$$\therefore \quad \frac{JK}{KL} = \frac{OX}{OC} = \frac{43.2}{300} = 0.144$$

Now $\dfrac{JL}{KL} = \dfrac{KL + JK}{KL} = 1 + \dfrac{JK}{KL} = 1 + 0.144 = 1.144$ **Ans.**

Again we know that

$$OY = \frac{JL}{KL} \times \frac{FD}{FG} \times OE$$

$\therefore \quad \dfrac{FG}{FD} = \dfrac{JL}{KL} \times \dfrac{OE}{OY} = 1.144 \times \dfrac{115}{69.1} = 1.9$ **Ans.**

EXERCISES

1. A *D*-slide valve has a travel of 100 mm, angle of advance 30º and the exhaust lap at both ends of the valve is 12 mm. The cut-off takes place at 85% of the stroke on the cover end of the cylinder. Determine the lead and the point of release for this stroke.
If the lead is same for both the ends, find the point of cut-off on the crank end and the steam lap. The length of the connecting rod is 4 times the crank length.
[Ans. 7.2 mm; 98% of stroke, 78% of stroke, 18 mm]

2. The travel of a slide valve is 100 mm and the lead at the crank end is 6 mm. If the length of connecting rod is 4.5 times the crank length, find the angle of advance, steam lap and exhaust lap to give cut-off and release at 65% and 95% of the stroke respectively. **[Ans. 38°, 24 mm, 12 mm]**

3. The following data refer to a *D*-slide valve :
Valve travel = 150 mm; Lead at cover end = 6 mm ; Connecting rod length = 5 times crank length; Cut-off at both ends of the piston = 0.7 stroke
Determine the angle of advance of the eccentric and maximum opening of port to steam and steam lap for the cover end. Find also the steam lap and lead for the crank end of the valve.
[Ans. 40°, 35 mm; 40 mm; 26 mm; 22 mm]

4. A simple slide valve with outside admission provides a lead of 3 mm, a maximum port opening of 18 mm and a cut-off at 62% at the out-stroke (*i.e.* at the crank end). The ratio of the connecting rod length to the crank radius is 3.7. Find the valve travel, steam lap and the angle of advance. If the exhaust lap is 12.5 mm, find the percentage of stroke at which release and compression will occur.
[Ans. 78 mm, 20 mm, 37º; 92.5% of forward stroke, 88% of return stroke]

5. A steam engine fitted with a *D*-slide valve gives a cut-off at 65% of the stroke and release at 90% of the stroke for both ends of the cylinder. The width of the ports is 25 mm, maximum opening of port to steam is 18 mm and the valve lead at the cover end is 6 mm. If the length of the connecting rod is 5 times the crank length, find the total valve travel and the angle of advance of the eccentric. Determine also the valve lead at the crank end and the steam and exhaust laps for both ends of the cylinder.
[Ans. 88 mm, 45.5; *l* (crank end) = 14 mm, *s* (cover end) = 25 mm, (crank end) = 17.5 mm, *e* (cover end) = 6.5 mm, *e* (crank end) = 10.8 mm]

6. The following particulars refer to a Meyer's expansion valve :
Angle of advance of main eccentric = 35º; Travel of main valve = 150 mm; Angle of advance of expansion eccentric = 90º; Throw of expansion eccentric = 75 mm ; Ratio of connecting rod length to crank length = 4.
Find the steam laps required at the two ends of the expansion valve in order to give cut-off at 0.2, 0.4 and 0.6 of the stroke on both strokes. Determine also the best setting of the expansion plates.
[Ans. 24 mm, 48 mm, 64 mm for cover end; 38 mm, 60 mm, 68 mm for crank end]

7. The dimensions of a Hackworth valve gear, as shown in Fig. 17.34 (Page 645) are as follows :
OC = 300 mm; *CP* = 700 mm; *OE* = 145 mm; *ED* = 800 mm and *EA* = 550 mm.
The die block *D* coincides with *F* when the crank is at dead centres. Find the throw and the angle of advance of the equivalent eccentric when the inclination of the slotted link is 30º with the vertical.
[Ans. 73.3 mm; 38.2º]

8. The Walschaert radial valve gear of a locomotive engine in which the slide valve has inside admission, is shown in Fig. 17.43. The main crank *OC* is 250 mm and the crank *OE* is 75 mm.

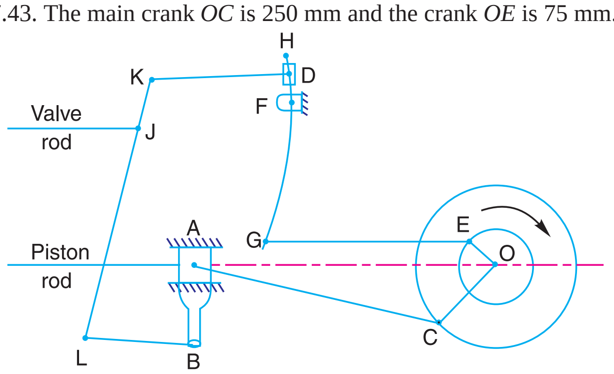


Fig. 17.43

If $DE = 0.6\ FG$ and $JK = 0.15\ JL$, find the travel of the valve. When the cut off is to take place at 60% of the stroke of the piston, find steam lap and lead of the valve. The motion of points K and L may each be assumed simple harmonic along a horizontal straight line.

[Ans. 100 mm, 32.5 mm, 0.75 mm]

DO YOU KNOW ?

1. State the function of a valve in a steam engine. Name the types of valves commonly used to control the various operations in a steam engine.
2. Describe the action of a *D*-slide valve and piston slide valve. Discuss the advantages of a piston slide valve over *D*-slide valve.
3. Define steam lap, exhaust lap and angle of advance for a simple slide valve with 1. out-side steam admission, and 2. inside steam admission.
4. Explain how the ponts of admission, cut-off, release and compression are determined for a *D*-slide valve using any one of the following constructions :
   1. Zeuner valve diagram. 2. Reuleaux valve diagram, and 3. Bilgram valve diagram.
5. Discuss with the help of diagrams, the disadvantages of earlier cut-off with a simple slide valve.
6. Explain with the help of a neat sketch, the function of a Meyer's expansion valve in a steam engine.
7. What do you understand by virtual or equivalent eccentric? How it is obtained for the Meyer's expansion valve?
8. Why the reversing gears are used in steam engines? State the commonly used types of reversing gears and how they differ from one another?
9. Describe, with the help of a line diagram, the working of a Stephenson link motion. How the virtual eccentric and its angle of advance for any setting of this link motion is determined?
10. Discuss the principle underlying the use of a radial valve gear.
11. Explain, with the help of a line diagram, the working of a Hackworth valve gear. Discuss the method to determine the virtual eccentric and its angle of advance for this gear.
12. Describe, with the help of a line diagram, the working of a Walschaert's valve gear. How will you determine the virtual eccentric and its angle of advance for this gear?

OBJECTIVE TYPE QUESTIONS

1. In a steam engine, the distance by which the outer edge of the *D*-slide valve overlaps the steam port is called
   (*a*) lead (*b*) steam lap
   (*c*) exhaust lap (*d*) none of these
2. The *D*-slide valve is also known as
   (*a*) inside admission valve (*b*) outside admission valve
   (*c*) piston slide valve (*d*) none of these
3. In Meyer's expansion valve, main valve is driven by an eccentric having an angle of advance
   (*a*) 10º – 15º (*b*) 15º – 25º
   (*c*) 25º – 30º (*d*) 30º – 40º
4. In Meyer's expansion valve, the expansion valve is driven by an eccentric having an angle of advance
   (*a*) 50º – 60º (*b*) 60º – 70º
   (*c*) 70º – 80º (*d*) 80º – 90º
5. The function of a reversing gear in a steam engine is
   (*a*) to control the supply of steam
   (*b*) to alter the point of cut-off while the engine is running
   (*c*) to reverse the direction of motion of the crankshaft
   (*d*) all of the above

ANSWERS

1. (*b*) **2.** (*b*) **3.** (*c*) **4.** (*d*) **5.** (*b*),(*c*)

GO To FIRST