receiver volumes. Taking the simplest case—that of a tandem engine, or of an engine with parallel cylinders whose pistons move together or in opposition—we may proceed thus. Since the point of cut-off to be determined depends on volume ratios we may for brevity treat the volume of the small cylinder as unity. Let R be the ratio to it of the receiver’s volume, and L that of the low- pressure cylinder. Let *x* be the required fraction of the stroke at which cut-off is to occur in the large cylinder ; and let *p* be the pressure at release from the small cylinder. As there is to be no drop, *p* is also the pressure in the receiver at the beginning of admission to the large cylinder. During that admission the volume changes from 1 + R to 1 - *x*: + R + *x*L, and the pressure at cut-off is

therefore *p*(1+R)/1-*x*+R+*x*L.The steam that remains is now compressed into the receiver, from volume 1 - *x* + R to volume R. Its pressure therefore rises to *p*(1+R)/1-*x*+R+*x*L·(1-*x*+R)/R, and this, by assumption, is to be equal to *p*. We therefore have

(1 + R)(1-*x*+R) = R(l - *x* + R + *x*L), whence *x*=(R + l)∕(RL + l).

Thus, with R = 1 and L = 3, cut-off should occur in the large cylinder at half-stroke ; with a greater cylinder ratio the cut-off should be earlier.

A similar calculation@@1 for a compound engine whose cranks are at right angles, and in which cut-off occurs in the large cylinder before half-stroke, shows that the condition of no drop is secured when

2R(*x*L-1) = 1 - 2√*x*(l *-x*)*.*

In some compound engines a pair of high-pressure cylinders dis­charge into a common receiver; in some a pair of low-pressure cylinders are fed from a receiver which takes steam from one high- pressure cylinder, or in some instances from two. With these arrangements the pressure in the receiver may be kept much more nearly constant than is possible with the ordinary two-cylinder type.

116. An important mechanical advantage belongs to the com­pound engine in the fact that it avoids the extreme thrust and pull which would have to be borne by the piston-rod of a single-cylinder engine working at the same power with the same initial pressure and the same ratio of expansion. If all the expansion took place in the low-pressure cylinder, the piston at the beginning of the stroke would be exposed to a thrust much greater than the sum of the thrusts on the two pistons of a compound engine in which a fair proportion of the expansion is performed in the small cylinder. Thus in the tandem engine of fig. 29 the greatest sum of the thrusts will be found to amount to less than two-thirds of the thrust which the large piston would be subjected to if the engine were simple. The mean thrust throughout the stroke is of course not affected by compounding; only the range of variation in the thrust is reduced. The effort on the crank-pin is consequently made more uniform, the strength of the parts may be reduced, and the friction at slides and journals is lessened. The advantage in this respect is obviously much greater when the cylinders are placed side by side, instead of tandem, and work on cranks at right angles. As a set-off to its advantage in giving a more uniform effort, the compound engine has the drawback of requiring more working parts than a simple engine with one cylinder. But in many instances—as in marine engines—two cranks and two cylinders are almost indis­pensable, to give a tolerably uniform effort and to get over the dead points ; and the comparison should then be made between a pair of simple cylinders and a pair of compounded cylinders. Another point in favour of the compound engine is that, although the whole ratio of expansion is great, there need not be a very early cut-off in either cylinder ; hence the common slide-valve, which is unsuited to give an early cut-off, may be used in place of a more complex arrangement. The mechanical advantage of the compound engine has long been recognized, and had much to do with its adoption in the early days of high-pressure steam.@@2 Its subsequent development has been due in part to this, but probably in much greater part to the thermodynamic advantage which has been discussed above (§ 93).

117. Indicator diagrams taken from compound engines show that the transfer of steam from one cylinder to another is never, under the most favourable con­ditions, performed without loss of energy. Fig. 33 shows a pair of diagrams from the two cylin­ders of a tandem Woolf engine, in which the steam passed as directly as possible from the small to the large cylinder. The diagrams are drawn to the same scale of *stroke* and therefore to different scales of *volume,* and the low-pressure diagram is turned round so that it may fit into the

high-pressure diagram. There is some drop at the high-pressure release, and, apart from this, there is a loss through friction of the passages, which shows itself by the admission line to the large cylinder lying below the exhaust line from the small one.

118. Fig. 31 is a pair of diagrams taken from a compound tandem re­ceiver engine running at 50 revolutions per minute, with cylinders 30 inches and 52 inches in diameter, and with a 6-feet stroke. The ratio of cylinder vol­umes is therefore 3 to 1. The capacity of the receiver is nearly 11/2 times that of the small cylinder. There is a comparatively early cut-off in both cylinders, and a nearly complete absence of drop.

The small cylinder, however, does more work than

the large one, in the ratio of nearly 3 to 2.

Fig. 35 shows the same pair of diagrams combined

by drawing both to the same scale of volume and of pressure, and by setting out each by an amount equal to the clearance space from the line of no volume. This makes the expansion curve in each diagram represent correctly the relation of the pres­sure to the absolute volume of the expanding steam. The broken line is a continuous curve of *adiabatic* expansion, drawn from the point of high-pressure cut-off, on the assumption that the steam then con­tained about 25 per cent. of condensed water. If the expansion were actually adiabatic, and if there were no loss in the transfer of the steam, the expansion curves for both cylinders would fall into this

line.

119. Fig. 36 exhi­bits, in the same manner as fig. 35, a set of diagrams taken by Mr Kirk from the triple expansion engines of the S.S. “Aber­deen.” Each diagram is set out from the line of no volume by a distance which represents the clearance in the corresponding cylinder. The boiler pressure is 125 lb per square inch. The cylinders are 32 inches, 46 inches, and 70 inches in diameter, and the stroke is 41/2 feet. The cranks make 120° with each other. The means of the diagrams for the two ends of each cylinder have been used in drawing this and the next figure, a practice which should be followed in drawing combined diagrams of the kind here ex­

emplified.

120. Fig. 37

shows in the same way a set of dia­grams taken by Mr Brock from the *quadruple* expan­sion engines of the S.S. “Lohara” (by Messrs Denny & Co.). Here the boiler pressure was 154 lb by gauge, or 169 lb absolute, the cylinders were 24 inches, 34inches, 48 inches, and 68 inches in diameter, the stroke was 4 feet, and the number of revolutions

65 per minute.

121. In all of these cases

a continuous curve, shown

by a broken line, has been drawn to re­present the re­sult of adia­batic expansion, on the same assumption as before—that the steam contains about 25 per cent. of water at the point of cut-off in the

@@@1 Examples of calculations dealing with particular arrangements of two and three cylinder compound engines will be found in an Appendix to Mr R. Sennett’s *Treatise on the Marine Steam Engine.*

@@@2 See a paper by Dr W. Pole, “ On the Double Cylinder Expansive Engine,” *Proc. Inst. M.E.,* 1862.