THE COMPOUND ENGINE

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LECTURE X.—THE COMPOUND ENGINE.

BY F. R. LOW.

Before we commence the study of the compound engine let us brush up a little regarding expansion and the gains and losses attending it.

As the volume of steam is expanded its pressure falls and practically in an inverse ratio; that is, if you double the volume you halve the pressure, if you treble the volume you have one-third the pressure, etc., only remember that you must work with absolute pressures, not gage pressures.

If you will consider that statement a little you will find that it means that the product of the volume and the pressure is constant. Suppose you have a cubic foot of steam at 120 pounds (absolute). Expand it to two cubic feet and the pressure will be 60, but you have two of the original volumes and 2×60 is 120. If you expand it to three cubic feet the pressure will fall to 40 pounds, but the product of this pressure and the three volumes is still 120, and however far we may expand it will be true that, counting the original volume as 1, the pressure times the number of volumes to which we have expanded will equal the initial pressure. The number of times that the original volume is contained in the final volume is called the "ratio of expansion." If we take one cubic foot of steam and expand it to four cubic feet the ratio of expansion is four, etc. From this principle you will easily see that we can derive the following:

RULES.

To find the ratio of expansion divide the final volume by the initial volume.

What is the ratio of expansion when two cubic feet of steam are expanded to eleven cubic feet?

$$11 \div 2 = 5.5$$

To find the terminal pressure divide the initial pressure by the ratio of expansion.

EXAMPLE—Steam of 75 pounds gage pressure is expanded to six times its original volume. What will its pressure be?

A gage pressure of 75 pounds is 75+15=90 absolute, approximately, and 90÷6=15 pounds absolute or zero gage.

To find the initial pressure multiply the terminal pressure by the ratio of expansion.

EXAMPLE—In an engine cylinder steam is expanded to 4.5 times its volume at cut-off, the pressure at the end of the stroke being 18 pounds absolute. What is the initial pressure?

4.5×18=81 pounds absolute, or 81—15=66 pounds gage.

In Fig. 1 let o *x* represent the absolute zero of pressure and *o A* the zero of volume. Suppose we have a volume of steam proportional to *A B* or o 1 at 120 pounds absolute. If it is expanded to twice its original volume its volume will be represented by the line o 2 and its pressure will be 120÷2=60 pounds. Setting off 60 pounds on the 2d ordinate we have the point *a* as representing its pressure at this volume. If it is expanded to three times its original size its volume will be bounded by the ordinate 3 and on this ordinate we set off the pressure 120÷3=40 pounds, locating the point *b*. Locating in the same manner the points *c d e f g*, representing the pressures at successive volumes, we find that if joined together they form a curve which constantly approaches, but never reaches the zero line. We can locate as many points on this curve as we like. For instance, when the volume has expanded to 1½ the pressure will be 120÷1.5=80 pounds, which set off on the corresponding ordinate gives us the point *h*. This curve is called an hyperbola, and represents, when

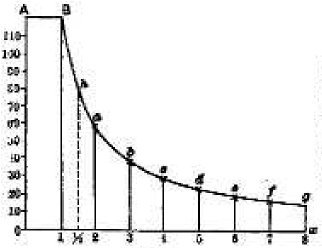

FIG. 1.

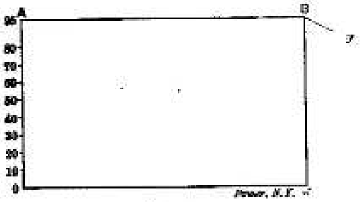

FIG. 2.

used in this way, the gradual decrease of pressure when steam is cut off and expanded in an engine cylinder.

Power, you know, is force exerted through space. In Fig. 2 we have a force of 80 pounds gage (95 pounds absolute) exerted throughout the stroke *o x*. The force is proportional to the height of the line *o A*; the space through which it is exerted is proportional to the length of the line *o x*, the power which is the product of the force and space is proportional then to the product of *o A* and *o x*, which is the area of the rectangle *o A B x*.

Now suppose that instead of carrying the steam the full length of the stroke we cut it off at half stroke. Then during the remainder of the stroke the pressure will fall off along the line *B C*, Fig. 3. and the power will be proportional to the area *A B C x D O*. We have used only half the quantity of steam, but with the exception of the corner *B E C* have got as much power as before. The area *B C x D* is all gain, so you see there is a very great economy in cutting off at half stroke over carrying steam full stroke.

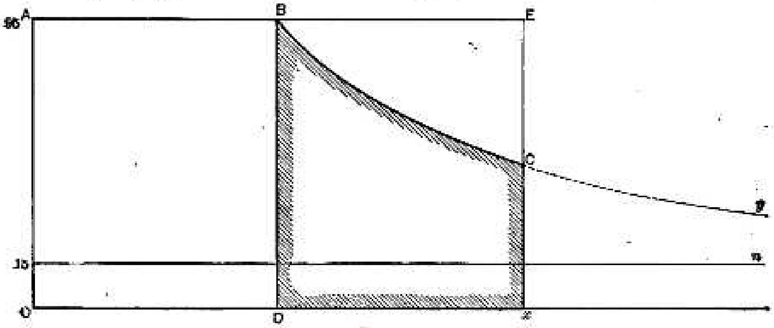

FIG. 3.

Now suppose that instead of cutting off at one-half stroke as in Fig. 3 we cut off at one-quarter as in Fig. 4. Here again the power is proportional to *A B C x D O*. The area *B C x D* is gain from expansion. We have used half as much steam as in Fig. 3 and lost the area *B F, G C*. There is still a distinct gain, but rather less than before. In Fig. 3 with half the steam we got in the diagram *A B C x D O* 85 per cent. of the power we would have got if we carried steam the full stroke. In Fig. 4, we halve the steam again and still get about 70 per cent. of what we got with double the quantity in Fig. 3, and about 60 per cent. of what we got with four times as much steam in Fig. 2.

When the steam follows full stroke all its expansive power is sacrificed and we lose the area which would be included between the diagram and the dotted line *B Y* Fig. 1 if that dotted line were extended until it met the back pressure line, which would be somewhat higher than the line *O x* even with a condensing engine. When expansion is introduced this loss is lessened. If *C y* in Fig. 3 were extended to meet a back pressure, line, *m n* at atmospheric pressure, the area would be obviously smaller, and in Fig. 4 the area is shown to be smaller still. In all the diagrams the volume to be filled with steam is proportional to the line *A B*, and the power is proportional to the area of the diagram and theoretically the line *A B* will be shortest per unit of area of diagram, i. e., the volume of steam called for will be least per unit of power developed, when the expansion line just meets the line of back pressure, and the diagram ends in a point as in Fig. 5, in other words when the terminal pressure just equals the back pressure. The number of expansions necessary to do this can easily be found, by dividing the absolute initial pressure by the absolute back pressure.

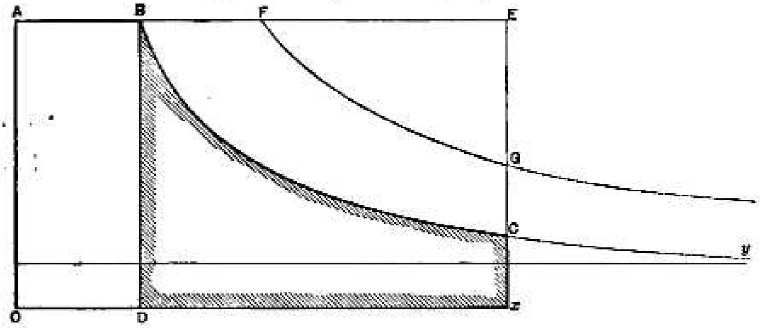

FIG. 4.

There are several reasons why this theoretical consideration does not hold good in practice. In the first place, if you had your steam given to you it would still cost you something to run an engine. There is the interest on the investment, depreciation, repairs, attendance, oil, waste, etc. The sum of these fixed charges ***per horse power*** for a given engine will be least when the engine is delivering the greatest number of horse-power, or in other words, when it has the greatest mean effective pressure. But the earlier the cut-off, the less the mean effective pressure, the less the horse-power, and the greater the fixed charges per horse power. This factor is not of extreme importance, however, for the fixed charges would not be very much greater for a larger engine out of which we could get the same horse-power, with a lower mean effective, and the earlier cut-off. The principal difficulty comes from cylinder condensation, which was considered somewhat at length in the last lecture. The incoming steam at a temperature due to the boiler pressure strikes against the cylinder walls which have just been exposed to the exhaust temperature and condenses until enough heat is given up to heat the surfaces up to the temperature of the incoming steam. The steam so condensed is re-evaporated for the most part on the exhaust-stroke, and thus gets through the cylinder without doing any work. The amount of this condensation depends upon the change in the temperature of the cylinder walls. If the cylinder could be made of a non-conducting material, a material which was slow to absorb and radiate heat, there would be little condensation. You know that polished surfaces radiate and absorb less than rough ones, and on several recent high grade engines the inside of the cylinder heads, the piston heads and all the surfaces exposed to live steam in the cylinder have been highly finished with beneficial results. The shorter the time required for the revolution

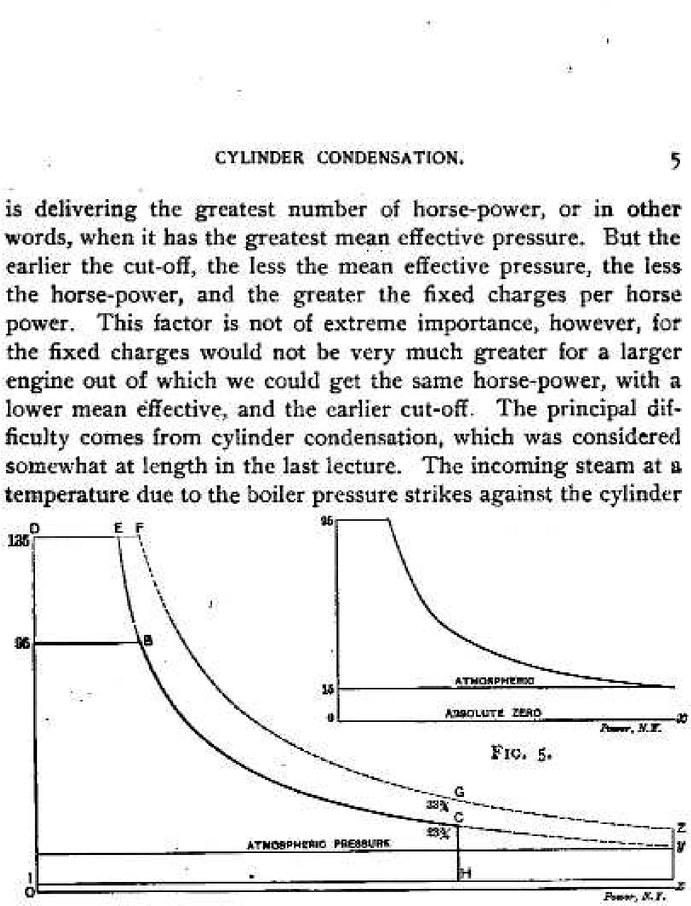

FIG. 5.

FIG. 6.

the less the condensation. While it is true that whether the engine runs fast or slow the walls will be exposed half of the time to the temperature of the steam and half to the temperature of the exhaust, it is also true that the temperature of the walls will vary least when the revolution is completed in the shortest time.

As the steam expands its temperature decreases and the surfaces begin to cool, continuing to do so throughout the expansion and the exhaust stroke. The longer it takes to make the revolution the cooler these surfaces will get. In a pumping engine making 30 revolutions a minute the surfaces are exposed to the exhaust temperature for a full second, and to a temperature below the initial for the greater part of another second during the working stroke. In an engine running 300 revolutions per minute the surfaces have only one-tenth the time in which to heat and cool, the variation of temperature is less and less steam is condensed in raising their temperature. The surfaces never get up to the temperature of the steam nor down to that of the exhaust, but vary back and forth through an intermediate range, the magnitude of which depends largely on the time of exposure. Experiments made by Messrs. Gately and Kletsch upon an unjacketed simple engine at Sandy Hook showed that the condensation varied sensibly inversely as the rotative speed.* Obviously, too, the emission of heat from the surfaces and the condensation necessary to restore their temperature will be greater with greater differences between the initial and exhaust temperatures, the higher the steam pressure and the lower the back pressure the greater the condensation.

The ratio of expansion has an important bearing on the percentage of loss by cylinder condensation. Not only is the actual amount of steam lost in this way increased with shorter cut-offs by the fact that the temperature is below that of the initial for a greater portion of the stroke, but as less steam is used per stroke with an early cut-off, the steam condensed in warming up the surfaces is a greater proportion of the total amount. Suppose you have an engine where the stroke is twice the diameter, which is a common proportion. When it is cutting off at one-quarter stroke the area of the cylinder wall exposed up to

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* A Manual of the Steam Engine. R. H. Thurston. Part 1, page 507. Journal Franklin Institute, October, 1885.
Cylinder Condensation.

cut-off will just equal the area of the piston head and the cylinder head.[†] In addition, there is the counter bore, ports, valve faces, etc., to be heated. Suppose it takes a cubic foot of steam to fill the cylinder up to the point of cut-off, and 20 per cent. more, or one-fifth of a cubic foot, is condensed to warm up the surfaces.

Now suppose that instead of cutting off at 1-4th, we cut off at 1-8th, we have nearly as much surface to heat up as before, and that surface will be cooler on account of the lesser temperature of the cylinder during the greater expansion, so that we shall still condense our one-fifth of a cubic foot to warm up the surfaces, but, having warmed them up, we let only one-half a cubic foot through to do work and of this half a cubic foot one-fifth is 40 per cent. while it was only 20 per cent. of the cubic foot passed at quarter cut-off. The percentage of loss from cylinder condensation thus increases very rapidly with early cut-offs, and more than equals the gain from increased expansion. Experiments show that for simple engines at about 80 pounds pressure the least amount of steam will be required per horse-power when the cut-off takes place between one-fifth and one-quarter stroke.

If you will consult a steam table you will find that a pound of steam at 80 pounds gage, or say 95 pounds absolute pressure, contains 1180.7 heat units. A pound of steam of 120 pounds gage or 135 pounds absolute contains 1188.7 heat units. In other words, we have only to put 1188.7—1180.7=8 heat units more into a pound of steam to increase its pressure from 80 to 120. This is a very small percentage of the heat used, but see how much we have added to the power-producing possibilities of the steam. In Fig. 6 the heavy diagram represents the power theoretically obtainable from steam of 80 pounds gage 95 absolute, cut-off at one-quarter stroke with an absolute back pressure of 3 pounds corresponding to a vacuum of 24 inches. If by the addition of only 8 heat units per pound we raise the pressure to 120 pounds gage or 135 absolute, we can with the same terminal pressure and using the same amount of steam, add the area

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[†] The area of the two heads $= \frac{D^2\pi}{2}$. The stroke equals 2 diameters so ¼ stroke $= \frac{D}{2}$ and this multiplied by the circumferance $D\pi = \frac{D^2\pi}{2}$ also.