CHAPTER VIII.

THE PHILOSOPHY OF THE STEAM-ENGINE.

ITS APPLICATION; ITS TEACHINGS RESPECTING THE CONSTRUCTION OF THE ENGINE AND ITS IMPROVEMENT.

"OFTENTIMES an Uncertaintie hindered our going on so merrily, but by persevering the Difficultie was mastered, and the new Triumph gave stronger Heart unto us."—RALEIGH.

"If everything which we cannot comprehend is to be called an impossibility, how many are daily presented to our eyes! and in contemning as false that which we consider to be impossible, may we not be depreciating a giant's effort to give an importance to our own weakness?"—MONTAIGNE.

"They who aim vigorously at perfection will come nearer to it than those whose laziness or despondency makes them give up its pursuit from the feeling of its being unattainable."—CHESTERFIELD.

As has been already stated, the steam-engine is a machine which is especially designed to transform energy, originally dormant or potential, into active and usefully available kinetic energy.

When, millions of years ago, in that early period which the geologists call the carboniferous, the kinetic energy of the sun's rays, and of the glowing interior of the earth, was expended in the decomposition of the vast volumes of carbonic acid with which air was then charged, and in the production of a life-sustaining atmosphere and of the immense forests which then covered the earth with their almost inconceivably luxuriant vegetation, there was stored up for the benefit of the human race, then uncreated, an inconceivably great treasure of potential energy, which we are now just beginning to utilize. This potential energy becomes kinetic and available wherever and whenever the powerful chemical affinity of oxygen for carbon is permitted to come into play; and the fossil fuel stored in our coal-beds or the wood of existing forests is, by the familiar process of combustion, permitted to return to the state of combination with oxygen in which it existed in the earliest geological periods.

The philosophy of the steam-engine, therefore, traces the changes which occur from this first step, by which, in the furnace of the steam-boiler, this potential energy which exists in the tendency of carbon and oxygen to combine to form carbonic acid is taken advantage of, and the utilizable kinetic energy of heat is produced in equivalent amount, to the final application of resulting mechanical energy to machinery of transmission, through which it is usefully applied to the elevation of water, to the driving of mills and machinery of all kinds, or to the hauling of "lightning" trains on our railways, or to the propulsion of the Great Eastern.

The kinetic heat-energy developed in the furnace of the steam-boiler is partly transmitted through the metallic walls which inclose the steam and water within the boiler, there to evaporate water, and to assume that form of energy which exists in steam confined under pressure, and is partly carried away into the atmosphere in the discharged gaseous products of combustion, serving, however, a useful purpose, *en route*, by producing the draught needed to keep up combustion.

The steam, with its store of heat-energy, passes through tortuous pipes and passages to the steam-cylinder of the engine, losing more or less heat on the way, and there expands, driving the piston before it, and losing heat by the transformation of that form of energy while doing mechanical work of equivalent amount. But this steam-cylinder is made of metal, a material which is one of the best conductors of heat, and therefore one of the very worst possible substances with which to inclose anything as subtile and difficult of control as the heat pervading a condensible vapor like steam. The process of internal condensation and reëvaporation, which is the great enemy of economical working, thus has full play, and is only partly checked by the heat from the steam-jacket, which, penetrating the cylinder, assists by keeping up the temperature of the internal surface and checking the first step, condensation, which is an essential preliminary to the final waste by reëvaporation. The piston, too, is of metal, and affords a most excellent way of exit for the heat escaping to the exhaust side.

Finally, all unutilized heat rejected from the steam-cylinder is carried away from the machine, either by the water of condensation, or, in the non-condensing engine, by the atmosphere into which it is discharged.

Having traced the method of operation of the steam-engine, it is easy to discover what principles are comprehended in its philosophy, to learn what are known facts bearing upon its operation, and to determine what are the directions in which improvement must take place, what are the limits beyond which improvement cannot possibly be carried, and, in some directions, to determine what is the proper course to pursue in effecting improvements. The general direction of change in the past, as well as at present, is easily seen, and it may usually be assumed that there will be no immediate change of direction in a course which has long been preserved, and which is well defined. We may, therefore, form an idea of the probable direction in which to look for improvement in the near future.

Reviewing the operations which go on in this machine during the process of transformation of energy which has been outlined, and studying it more in detail, we may deduce the principles which govern its design and construction, guide us in its management, and determine its efficiency.

In the furnace of the boiler, the quantity of heat developed in available form is proportional to the amount of fuel burned. It is available in proportion to the temperature attained by the products of combustion; were this temperature no higher than that of the boiler, the heat would all passooff unutilized. But the temperature produced by a given quantity of heat, measured in heat-units, is greater as the volume of gas heated is less. It follows that, at this point, therefore, the fuel should be perfectly consumed with the least possible air-supply, and the least possible abstraction of heat before combustion is complete. High temperature of furnace, also, favors complete combustion. We hence conclude that, in the steam-boiler furnace, fuel should be burned completely in a chamber having non-conducting walls, and with the smallest air-supply compatible with thorough combustion; and, further, that the air should be free from moisture, that greatest of all absorbents of heat, and that the products of combustion should be removed from the furnace before beginning to drain their heat into the boiler. A fire-brick furnace, a large combustion-chamber with thorough intermixture of gases within it, good fuel, and a restricted and carefully-distributed supply of air, seem to be the conditions which meet these requisites best.

The heat generated by combustion traverses the walls which separate the gases of the furnace from the steam and water confined within the boiler, and is then taken up by those fluids, raising their temperature from that of the entering "feed-water" to that due the steam-pressure, and expanding the liquid into steam occupying a greatly-increased volume, thus doing a certain amount of work, besides increasing temperature. The extent to which heat mayothus be usefully withdrawn from the furnace-gases depends upon the conductivity of the metallic wall, the rate at which the water will take heat from the metal, and the difference of temperature on the two sides of the metal. Extended "heating-surface," therefore, a metal of high conducting power, and a maximum difference of temperature on the two sides of the separating wall of metal, are the essential conditions of economy here. The heating-surface is sometimes made of so great an area that the temperature of the escaping gases is too low to give good chimney-draught, and a "mechanical draught" is resorted to, revolving "fan-blowers" being ordinarily used for its production. It is most economical to adopt this method. The steam-boiler is generally constructed of iron—sometimes, but rarely, of cast-iron, although "steel," where not hard enough to harden or temper, is better in consequence ofoits greater strength and homogeneousness of structure, and its better conductivity. The maximum conductivity of flow of heat for any given material is secured by so designing the boiler as to secure rapid, steady, and complete circulation of the water within it. The maximum rapidity of transfer throughout the whole area of heating-surface is secured, usually, by takingothe feed-water into the boiler as nearly as possible at the point where the gases are discharged into the chimney-flue, withdrawing the steam nearer the point of maximum temperature of flues, and securing opposite directions of flow for the gases on the one side and the water on the other. Losses of heat from the boiler, by conduction and radiation to surrounding bodies, are checked as far as possible by non-conducting coverings.

The mechanical equivalent of the heat generated in the boiler is easily calculated when the conditions of working are known. A pound of pure carbon has been found to be capable of liberating by its perfect combustion, resulting in the formation of carbonic acid, 14,500 British thermal units, equivalent to $14{,}500 \times 772 = 11{,}194{,}000$ foot-pounds of work, and, if burned in oneohour, to $\frac{11194000}{1980000} = 5.6$ horse-power. In other words, with perfect utilization, but $\frac{1}{5.6} = 0.177$, or about one-sixth, of a pound of carbon would be needed per hour for each horse-power of work done. But even good coal is not nearly all carbon, and has but about nine-tenths this heat-producing power, and it is usually rated as yielding about 10,000,000 foot-pounds of work per pound. The evaporative power of pure carbon being rated at 15 pounds of water, that of good coal may be stated at $13\frac{1}{2}$. In metric measures, one gramme of good coal should evaporate about $13\frac{1}{2}$ grammes of water from the boiling-point, producing the equivalent of about 3,000,000 kilogrammetres of work from the 7,272 *calories* of heat thus generated. A gramme of pure carbon generates in its combustion 8,080 *calories* of heat. Per hour and per horse-power, 0.08, or less than one-twelfth, of a kilogramme of carbon burned per hour evolves heat-energy equal to one horse-power.

Of the coal burned in a steam-boiler, it rarely happens that more than three-fourths is utilized in making steam; 7,500,000 foot-pounds (1,036,898 kilogrammetres) is, therefore, as much energy as is usually sent to the engine per pound of good coal burned in the steam-boiler. The "efficiency" of a good steam-boiler is therefore usually not far from 0.75 as a maximum. Rankine estimates this quantity for ordinary boilers of good design and with chimney-draught at

$$E = \frac{0.92}{1 + 0.5\frac{F}{S}};$$

in which $\frac{F}{S}$ is the ratio of weight of fuel burned per square foot of grate to the ratio of heating to grate surface; this is a formula of fairly close approximation for general practice.

The steam in the engine first drives the piston some distance before the induction or steam valve is closed, and it then expands, doing work, and condensing in proportion to work done as the expansion proceeds, until it is finally released by the opening of the exhaust or eduction valve. Saturated steam is modified in its action by a process which has already been described, condensing at the beginning and reëvaporating at the end of the stroke, thus carrying into the condenser considerable quantities of heat which should have been utilized in the development of power. Whether this operation takes place in one cylinder or in several is only of importance in so far as it modifies the losses due to conduction and radiation of heat, to condensation and reëvaporation of steam, and to the friction of the machine. It has already been seen how these losses are modified by the substitution of the compound for the single-cylinder engine.

The laws of thermo-dynamics teach, as has been stated, that the proportion of the heat-energy contained in the steam or other working fluid which may be transformed into mechanical energy is a fraction, $\frac{H_1 - H_2}{H_1}$, of the total, in which H_1 and H_2 are the quantities of heat contained in the steam at the beginning and at the end of its operation, measuring from the absolute zero of heat-motion. In perfect gases,

$$\frac{H_1 - H_2}{H\rho} = \frac{\tau_1 - \tau_2}{\tau_1} = \frac{T_1 - T_2}{T_1 + 461.2^\circ \text{ Fahr.}};$$

but in imperfect gases, and especially in vapors which, like steam, condense, or otherwise change their physical state, this equality may still exist, $\frac{H_1 - H_2}{H_1} = \frac{\tau_1 - \tau_2}{\tau_1'}$; and the fluid is equally efficient with the perfect gas as a working substance in a heat-engine. In any case it is seen that the efficiency is greatest when the whole of the heat is received at the maximum and rejected at the minimum attainable temperatures.

Assuming this expression strictly accurate, a hot-air engine working from 413.6° Fahr. or 874.8° absolute temperature, down to 122° Fahr. or 583.2° absolute, should have an efficiency of 0.263, transforming that proportion of available heat into mechanical work. The engines of the steamer Ericsson closely approached this figure, and gave a horse-power for each 1.87 pound of coal burned per hour.

Steam expands in the steam-cylinder quite differently under different circumstances. If no heat is either communicated to it or abstracted from it, however, it expands in an hyperbolic curve, losing its tension much more rapidly than when expanded without doing work, in consequence both of its change of volume and its condensation. The algebraic expression for this method of expansion is, according to Rankine, $PV^{1.111} = C$, a constant, or, according to other authorities, from $PV^{1.135} = C$ to $PV^{1.140} = C$. The greater the value of the exponent of V, the greater the efficiency of the fluid between any two temperatures. The maximum value has been found to be given where the steam is saturated, but perfectly dry, at the commencement of its expansion. The loss due to condensation on the cooled interior surface of the cylinder at the commencement of the stroke and the subsequent reëvaporation as expansion progresses is least when the cylinder is kept hot by its steam-jacket and when least time is given during the stroke for this transfer of heat between the metal and the vapor.

It may be said that, all things considered, therefore, losses of heat in the steam-cylinder are least when the steam enters dry, or moderately superheated, where the interior surfaces are kept hottest by the steam-jacket or by the hot-air jacket sometimes used, and where piston-speed and velocity of rotation are highest.[1] The best of compound engines, using steam of seventy-five pounds pressure and condensing, usually require about two pounds of coal per hour—20,000,000 foot-pounds of energy at the furnace—to develop a horse-power, i. e., about ten times the heat-

[1] In some cases, as in the Allen engine, the speed of piston has become very high, approaching $800\sqrt[3]{\text{stroke}}$.

equivalent of the mechanical work which they accomplish. Were the steam to expand like the permanent gases, they would have a theoretical efficiency of about one-quarter; actually, the efficiency is only one-tenth. The steam-engine, therefore, utilizes about two-fifths the heat-energy theoretically available with the best type of engine in general use. By far the greater part, nearly all, in fact, of the nine-tenths wasted is rejected in the exhaust steam, and can only be saved by some such method as is hereafter to be suggested of retaining that heat and returning it to the boiler.

The mechanical power which has now been communicated to the mechanism of the engine by the transfer of the kinetic energy of the hot steam to the piston is finally usefully applied to whatever "mechanism of transmission" forms the connection with the machinery driven by the engine. In this transfer, there is some loss in the engine itself, by friction. This is an extremely variable amount, and it can be made very small by skillful design and good workmanship and management. It may be taken at one-half pound per square inch of piston for good engines of 100 horse-power and upward, but is often several pounds in very small engines. It is least when the rubbing surfaces are of different materials, but both of smooth, hard, close-grained metal, well lubricated, and where advantage is taken of any arrangement of parts which permits the equilibration of pressure, as on the shaft-bearings of double and triple engines. The friction of a steam-engine of large size and good design is usually between five and seven per cent. of its total power. It increases rapidly as the size of engine decreases. The condensing apparatus doubles these figures.

Having now traced somewhat minutely the growth of the steam-engine from the beginning of the Christian era to the present time, having rapidly outlined the equally gradual, though intermittent, growth of its philosophy, and having shown how the principles of science find application in the operation of this wonderful machine, we are now prepared to study the conditions which control the intelligent designer, and to endeavor to learn what are the lessons taught us by science and by experience in regard to the essential requisites of efficient working of steam and economy in the consumption of fuel. We may even venture to point out definitely the direction in which improvement is now progressing as indicated by a study of these requisites, and may be able to perceive the natural limits to such progress, and possibly to conjecture what must be the character of that change of type which only can take the engineer beyond the limit set to his advance so long as he is confined to the construction of the present type of engine.

First, we must consider the question: *What is the problem, stated precisely and in its most general form, that engineers have been here attempting to solve?*

After stating the problem, we will examine the record with a view to determine what direction the path of improvement has taken hitherto, to learn what are the conditions of efficiency which should govern the construction of the modern steam-engine, and, so far as we may judge the future by the past, by inference, to ascertain what appears to be the proper course for the present and for the immediate future. Still further, we will inquire, what are the conditions, physical and intellectual, which best aid our progress in perfecting the steam-engine.

This most important problem may be stated in its most general, yet definite, form as follows:

To construct a machine which shall, in the most perfect manner possible, convert the kinetic energy of heat into mechanical power, the heat being derived from the combustion of fuel, and steam being the receiver and the conveyer of that heat.

The problem, as we have already seen, embodies two distinct and equally important inquiries:

The first: What are the scientific principles involved in the problem as stated?

The second: How shall a machine be constructed that shall most efficiently embody, and accord with, not only those scientific principles, but also all of those principles of engineering practice that so vitally affect the economical value of every machine?

The one question is addressed to the man of science, the other to the engineer. They can be satisfactorily answered, even so far as our knowledge at present permits, after studying with care the scientific principles involved in the theory of the steam-engine under the best light that science can afford us, and by a careful study of the various steps of improvement that have taken place and of accompanying variations of structure, analyzing the effect of each change, and tracing the reasons for them.

The theory of the steam-engine is too important and too extensive a subject to be satisfactorily treated here in even the most concise possible manner. I can only attempt a plain statement of the course which seems to be pointed out by science as the proper one to pursue in the endeavor to increase the economical efficiency of steam-engines.

The teachings of science indicate that *success in economically deriving mechanical power from the energy of heat-motion will, in all cases, be the greater as we work between more widely separated limits of temperature, and as we more perfectly provide against losses by dissipation of heat in directions in which it is unavailable for the production of power.*

Scientific research, as we have seen, has proved that, in all known varieties of heat-engine, a large loss of effect is unavoidable from the fact that we cannot, in the ordinary steam-engine, reduce the lower limit of temperature, in working, below a point which is far above the absolute zero of temperature—far above that point at which bodies have no heat-motion. The point corresponding to the mean temperature of the surface of the earth is above the ordinary lower limit.

The higher the temperature of the steam when it enters the steam cylinder, and the lower that which it reaches before the exhaust occurs, the greater, science tells us, will be our success, provided we at the same time avoid waste of heat and power.

Now, looking back over the history of the steam-engine, we may briefly note the prominent improvements and the most striking changes of form, and may thus endeavor to obtain some idea of the general direction in which we are to look for further advance.

Beginning with the machine of Porta, at which point we may first take up an unbroken thread, it will be remembered that we there found a single vessel performing the functions of all the parts of a modern pumping-engine; it was, at once, boiler, steam-cylinder, and condenser, as well as both a lifting and a forcing pump.

The Marquis of Worcester divided the engine into two parts, using a separate boiler.

Savery duplicated that part of the engine of Worcester which performed the several parts of pump, steam-cylinder, and condenser, and added the use of water to effect rapid condensation, perfecting, so far as it was ever perfected, the steam-engine as a simple machine.

Newcomen and Calley next separated the pump from the steam-engine proper, producing the modern steam-engine—the engine as a train of mechanismq and in their engine, as in Savery's, we noticed the use of surface condensation first, and subsequently that of the jet thrown into the midst of the steam to be condensed.

Watt finally effected the crowning improvements, and completed the movement of "differentiation" by separating the condenser from the steam-cylinder. Here thisoprocess of change ceased, the several important operations of the steam-engine now being conducted each in a separate vessel. The boiler furnished the steam, the cylinder derived from it mechanical power, and it was finally condensed in a separate vessel, while the power which had been obtained from it in the steam-cylinder was transmitted through still other parts, to the pumps, or wherever work was to be done.

Watt, also, took the initiative in another direction. He continually increased the efficiency of the machine by improving the proportions of its parts and the character of its workmanship, thus making it possible to render available many of those improvements in detail upon which effectiveness is so greatly dependent and which are only useful when made by a skillful workman.

Watt and his contemporaries also commenced that movement toward higher pressures of steam and greater expansion which has been the most striking feature noticed in the progress of steam-engineering since his time. Newcomen used steam of barely more than atmospheric pressure and raised 105,000 pounds of water one foot high with a pound of coal consumed. Smeaton raised the pressure somewhat and increased the duty considerably. Watt started with a duty double that of Newcomen and raised it to 320,000 foot-pounds per pound of coal, with steam at 10 pounds pressure. To-day, Cornish engines of the same general plan as those of Watt, but worked with 40 to 60 pounds of steam and expanding three or four times, do a duty probably averaging, with the better class of engines, 600,000 foot-pounds per pound of coal. The triple-expansion engine runs the figure up to above 1,500,000.

The increase in steam-pressure and in expansion since Watt's time has been accompanied by a very great improvement in workmanship—a consequence, very largely, of the rapid increase in perfection, and in the wide range of adaptation of machine-tools—by higher skill and intelligence in designing engines and boilers, by increased piston-speed, greater care in obtaining dry steam, and in keeping it dry until thrown out of the cylinder, either by steam-jacketing or by superheating, or both combined; it has further been accompanied by a greater attention to the important matter of providing carefully against losses by radiation and conduction of heat. We use, finally, the compound or multiple cylinder engine for the purpose of saving some of the heat usually lost in internal condensation and reëvaporation, and precipitation of condensed vapor from great expansion.

It is evident that, although there is a limit, tolerably well defined, in the scale of temperature, below which we cannot expect to pass, a degree gained in approaching this lower limit is more remunerative than a degree gained in the range of temperature available by increasing temperatures.[1]

Hence the attempt made by the French inventor, Du Trembly, about the year 1850, and by other inventors since, to utilize a larger proportion of heat by approaching more closely the lower limit, was in accordance with known scientific principles.

We may summarize the result of our examination of the growth of the steam-engine thus:

First. The process of improvement has been one, primarily, of "differentiation;"[2] the number of parts has been continually increased, while the work of each part has been simplified, a separate organ being appropriated to each process in the cycle of operations.

Secondly. A kind of secondary process of differentia-

[1] The fact here referred to is easily seen if it is supposed that an engine is supplied with steam at a temperature of 400° above absolute zero and works it, without waste, down to a temperature of 200°. Suppose one inventor to adapt the engine to the use of steam of a range from 500° down to 200°, while another works his engine, with equally effective provision against losses, between the limits of 400° and 100°, an equal range with a lower mean. The first case gives an efficiency of one-half, the second three-fifths, and the third three-fourths, the last giving the highest effect.

[2] This term, though perhaps not familiar to engineers, expresses the idea perfectly.

tion has, to some extent, followed the completion of the primary one, in which secondary process one operation is conducted partly in one and partly in another portion of the machine. This is illustrated by the two cylinders of the compound engine and by the duplication noticed in the binary engine.

Thirdly. The direction of improvement has been marked by a continual increase of steam-pressure, greater expansion, provision for obtaining dry steam, high piston-speed, careful protection against loss of heat by conduction or radiation, and, in marine engines, by surface condensation.

The direction which improvement seems now to be taking, and the proper direction, as indicated by an examination of the principles of science, as well as by our review of the steps already taken, would seem to beo working between the widest attainable limits of temperature.

Steam must enter the machine at the highest possible temperature, must be protectedd from waste, and must retain, at the moment before exhaust, the least possible amount of heat. He whose inventive genius, or mechanical skill, contributeso to effect either the use of higher steam with safety and without waste, or the reduction of the temperature of discharge, confers a boon upon mankind.

In detail: In the engine, the tendency is, and may probably be expected to continue, in the near future at least, toward higher steam-pressure, greater expansion in more than one cylinder, steam-jacketing, superheating, a careful use of non-conducting protectors against waste, and the adoption of still higher piston-speeds.

In the boiler: more complete combustion without excess of air passing through the furnace, and more thorough absorption of heat from the furnace-gases. The latter will probably be ultimately effected by the use of a mechanically produced draught, in place of the far more wasteful method of obtaining it by the expenditure of heat in the chimney.

In construction we may anticipate the use of better materials, and more careful workmanship, especially in the boiler, and much improvement in forms and proportions of details.

In management, there is a wide field for improvement, which improvement we may feel assured will rapidly take place, as it has now become well understood that great care, skill, and intelligence are important essentials to the economical management of the steam-engine, and that they repay, liberally, all of the expense in time and money that is requisite to secure them.

In attempting improvements in the directions indicated, it would be the height of folly to assume that we have reached a limit in any one of them, or even that we have approached a limit. If further progress seems checked by inadequate returns for efforts made, in any case, to advance beyond present practice, it becomes the duty of the engineer to detect the cause of such hinderance, and, having found it, to remove it.

A few years ago, the movement toward the expansive working of high steam was checked by experiments seeming to prove positive disadvantage to follow advance beyond a certain point. A careful revision of results, however, showed that this was true only with engines built, as was then common, in utter disregard of all the principles involved in such a use of steam, and of the precautions necessary to be taken to insure the gain which science taught us should follow. The hinderances are mechanical, and it is for the engineer to remove them.

The last remark is especially applicable to the work of the engineer who is attempting to advance in the direction in which, as already intimated, an unmistakable revolution is now progressing, the modification of the modern steam-engine to adapt it safely and successfully to run at the high piston-speed, and great velocity of rotation which have been already attained and which must undoubtedly be greatly exceeded in the future. As there is no known and definite limit to the economical increase of speed, and as the limit set by practical conditions is continually being set farther back as the builder acquires greater skill and attains greater accuracy of workmanship and the power to insure greater rigidity of parts and durability of wearing surfaces, we must anticipate a continued and indefinite progress in this direction—a progress which must evidently be of advantage, whatever may be the direction that other changes may take.

It is evident that this adaptation of the steam-engine to great speed of piston is the work now to be done by the engineer. The requisites to success are obvious, and may be concisely stated as follows:

1. Extreme accuracy in proportions.
2. Perfect accuracy in fitting parts to each other.
3. Absolute symmetry of journals.
4. Ample area and maximum durability of rubbing surfaces.
5. Perfect certainty of an ample and continuous lubrication.
6. A nicely calculated and adjusted balance of reciprocating parts.
7. Security against injury by shock, whether due to the presence of water in the cylinder or to looseness of running parts.
8. A "positive-motion" cut-off gear.
9. A powerful but sensitive and accurately-working governor determining the degree of expansion.[1]

[1] The author is not absolutely confident on the latter point. It may be found more economical and satisfactory, ultimately, to determine the point of cut-off by an automatic apparatus adjusting the expansion-gear *by reference to the steam-pressure*, regulating the speed by attaching the governor elsewhere. The author has devised several forms of apparatus of the kind referred to.

10. Well-balanced valves and an easy-working valve-gear.

11. Small volume of "dead-space," or "clearance," and properly adjusted "compression."

It would seem sufficiently evident that the engine with detachable ("drop") cut-off valve-gear must, sooner or later, become an obsolete type, although the substitution of springs or of steam-pressure for gravity in the closing of the detached valve may defer greatly this apparently inevitable change. The "engine of the future" will not probably be a "drop cut-off engine."

As regards the construction of the engine as a piece of mechanism, the principles and practice of good engineering are precisely the same, whether applied in the designing of the compound or of the ordinary type of steam-engine. The proportioning of the two machines to each other in such manner as to form an effective whole, by procuring approximately equal amounts of work from both, is the only essential peculiarity of compound-engine design which calls for especial care, and the method of securing success in practice may be stated to be, for both forms of engines, as follows:

1. A good design, by which is meant—

a. Correct proportions, both in general dimensions and in arrangement of parts, and proper forms and sizes of details to withstand safely the forces which may be expected to come upon them.

b. A general plan which embodies the recognized practice of good engineering.

c. Adaptation to the specific work which it is intended to perform, in size and in efficiency. It sometimes happens that good practice dictates the use of a comparatively uneconomical design.

2. Good construction, by which is meant—

a. The use of good material.

b. Accurate workmanship.

c. Skillful fitting and a proper "assemblage" of parts.

3. Proper connection with its work, that it may do that work under the conditions assumed in its design.

4. Skillful management by those in whose hands it is placed.

In general, it may be stated that, to secure maximum economical efficiency, steam should be worked at as high a pressure as possible, and the expansion should be fixed as nearly as possible at the point of maximum economy for that pressure. In general, the number of times which the volume of steam may be expanded in the standard single-cylinder, high-pressure engine with maximum economy, is not far from $\frac{1}{2}\sqrt{P}$, where P is the pressure in pounds per square inch; it rarely exceeds $0.75\sqrt{P}$. This may be exceeded in double-cylinder engines. It is even more disadvantageous to cut off too short than to "'follow' too far." With considerable expansion, steam-jacketing and moderate superheating should be adopted, to prevent excessive losses by internal condensation and reëvaporation; and expansion should take place in cylinders in series, to avoid excessive weight of parts, irregularity of motion, and great loss by friction, as well as to insure economy.

To secure this vitally important economy, it is advisable to seek some practicable method of lining the cylinder with a non-conducting material. This plan, as has been seen, was adopted by Smeaton, in constructing Newcomen engines a century ago. Smeaton used wood on his pistons, and Watt tried wood as a material for steam-cylinder linings. That material is too perishable at temperatures now common, and no metal has yet been substituted, or even discovered, which answers the same purpose. The loss will also be reduced by increasing the speed of rotation and velocity of piston. Where no effectual means can be found of preventing contact of the steam with a good absorbent and conductor of heat, it will be found best to sacrifice some of the efficiency due to the change of state of the vapor, by superheating it and sending it into the cylinder at a temperature considerably exceeding that of saturation. With low steam and slowly-moving pistons, it is better to pursue the latter course than to attempt to increase the efficiency of the engine by greater expansion.

External surfaces shonld be carefully covered by non-conductors and non-radiators, to prevent losses by conduction and radiation of heat. It is especially necessary to reduce back-pressure and to obtain the most perfect vacuum possible without overloading the air-pump, if it is desired to obtain the maximum efficiency by expansion, and it then becomes also very necessary to reduce losses by "dead-spaces" and by badly-adjusted valves.

The piston-speed should be as great as can be sustained with safety.

Good engines should not require more than $W = \frac{200}{\sqrt{P}}$, where $W =$ the weight of steam per hour and per horse-power; the best practice gives about $W = \frac{180}{\sqrt{P}}$ in large engines with dry steam, high piston-speed, and good design, construction, and management.

The expansion-valve gear should be simple. The point of cut-off is perhaps best determined by the governor. The valve should close rapidly, but without shock, and should be balanced, or some other device should be adopted to make it easy to move and free from liability to cutting or rapid wear.

The governor should act promptly and powerfully, and should be free from liability to oscillate, and to thus introduce irregularities which are sometimes not less serious than those which the instrument is intended to prevent.

Friction should be reduced as much as possible, and careful provision should be made to economize lubricants as well as fuel.

The Principles of Steam-Boiler Construction are exceedingly simple; and although attempts are almost daily made to obtain improved results by varying the designoand arrangement of heating-surface, the best boilers of nearly all makers of acknowledged standing are practically equal in merit, although of very diverse forms.

In making boilers, the effort of the engineer should evidently be :

1. To secure complete combustion of the fuel without permitting dilution of the products of combustion by excess of air.

2. To secure as high temperature of furnace as possible.

3. To so arrange heating-surfaces that, without checking draught, the available heat shall be most completely taken up and utilized.

4. To make the form of boiler such that it shall be constructed without mechanical difficulty or excessive expense.

5. To give it such form that it shall be durable, under the action of the hot gases and of the corroding elements of the atmosphere.

6. To make every part accessible for cleaning and repairs.

7. To make every part as nearly as possible uniform in strength, and in liability to loss of strength by wear and tear, so that the boiler when old shall not be rendered useless by local defects.

8. To adopt a reasonably high "factor of safetyö" in proportioning parts.

9. To provide efficient safety-valves, steam-gauges, and other appurtenances.

10. To secure intelligent and very careful management.

In securing complete combustion, the first of these desiderata, an ample supply of air and its thorough intermixture with the combustible elements of the fuel are essentialq for the second—high temperature of furnace—it is necessary that the air-supply shall not be in excess of that absolutely needed to give complete combustion. The efficiency of a furnace in making heat available is measured by

$$E = \frac{T - T'}{T - t};$$

in which E represents the ratio of heat utilized to the whole calorific value of the fuel, T is the furnace-temperature, T' the temperature of the chimney, and t that of the external air. The higher the furnace-temperature and the lower that of the chimney, the greater the proportion of heat available. It is further evident that, however perfect the combustion, no heat can be utilized if either the temperature of the chimney approximates to that of the furnace, or if the temperature of the furnace is reduced by dilution approximately to that of the boiler. Concentration of heat in the furnace is secured, in some cases, by special expedients, as by heating the entering air, or as in the Siemens gas-furnace, heating both the combustible gases and the supporter of combustion. Detached fire-brick furnaces have an advantage over the "fire-boxes" of steam-boilers in their higher temperature; surrounding the fire with non-conducting and highly heated surfaces is an effective method of securing high furnace-temperature.

In arranging heating-surface, the effort should be to impede the draught as little as possible, and so to place them that the circulation of water within the boiler should be free and rapid at every part reached by the hot gases. The directions of circulation of water on the one side and of gas on the other side the sheet should, whenever possible, be opposite. The cold water should enter where the cooled gases leave, and the steam should be taken off farthest from that point. The temperature of chimney-gases has thus been reduced in practice to less than 300° Fahr., and an efficiency equal to 0.75 to 0.80 the theoretical has been attained.

The extent of heating-surface simply, in all of the best forms of boiler, determines the efficiency, and in them the disposition of that surface seldom affects it to any great extent. The area of heating-surface may also be varied within very wide limits without very greatly modifying efficiency. A ratio of 25 to 1 in flue and 30 to 1 in tubular boilers represents the relative area of heating and grate surfaces as chosen in the practice of the best-known builders.

The material of the boiler should be tough and ductile iron, or, better, a soft steel containing only sufficient carbon to insure melting in the crucible or on the hearth of the melting-furnace, and so little that no danger may exist of hardening and cracking under the action of sudden and great changes of temperature.

Where iron is used, it is necessary to select a somewhat hard, but homogeneous and tough, quality for the fire-box sheets or any part exposed to flames.

The factor of safety is invariably too low in this country, and is never too high in Europe. Foreign builders are more careful in this matter than our makers in the United States. The boiler should be built strong enough to bear a pressure at least six times the proposed working-pressure ; as the boiler grows weak with age, it should be occasionally tested to a pressure far above the working-pressure, which latter should be reduced gradually to keep within the bounds of safety. In the United States, the factor of safety is seldom more than four in the new boilers, frequently much less, and even this is reduced practically to one and a third by the operation of our inspection-laws.

The principles just enunciated are those generally, perhaps universally, accepted principles which are stated in all text-books of science and of steam-engineering, and are accepted by both engineers and men of science.

These principles are correct, and the deductions which have been here formulated are rigidly exact, as applied to all types of heat-engine in use ; and they lead us to the determination, in all cases, of the "modulus" of efficiency of the engine, i. e., to the calculation of the ratio of its actual efficiency to that efficiency which it would have, were it absolutely free from loss of heat by conduction or radiation, or other method of loss of heat or waste of power, by friction of parts or by shock.

The best modern marine compound engines sometimes, as we have seen, consume as little as two pounds of coal per horse-power and per hour; but this is but about one-tenth the power derivable from the fuel, were all its heat thoroughly utilized. This loss may be divided thus: 70 per cent. rejected in exhausted steam; 20 per cent. lost by conduction and radiation and by faults of mechanism and design; and only the 10 per cent. remaining is utilized. Thirty per cent. of the heat generated in the furnace is usually lost in the chimney, and of the remainder, which enters the engine, 20 per cent. at most is all which we can hope to save any portion of by improvements effected in our best existing type of steam-engine. It has already been shown how the engineer can best proceed in attempting this economy.

The direction in which further improvement must take place in the standard type of engine is plainly that which shall most efficiently check losses by internal condensation and reëvaporation by the transfer of heat to and from the metal of the steam-cylinder. The condensation of steam doing work is evidently not a disadvantage, but, on the contrary, a decided advantage.

Novel types of engine can, if at all, probably only supersede the common form when engineers can employ steam of very high pressure, and adopt much greater range of expansion than is now usual. Great velocity of piston and high speed of rotation are also essential in the attempt to make any revolution in steam-engine construction a success.

When a new form of steam-engine is likely to be introduced, if at all, can be scarcely even conjectured. It seems evident that its success is to be secured, if a revolution is ever to occur, by the adoption of high steam-pressures, of great piston-speeds, by care and skill in design, by the use of exceptionally excellent materials of construction, by great perfection of workmanship, and by intelligence in its management.

Experiment and experience will probably lead gradually to the general and safe employment of much higher steam-pressures and piston-speeds and superheating, and may ultimately reveal and remove all those difficulties which must invariably be expected to be met here, as in all other attempts to effect radical changes, however important they may be.[1]

[1] *Vide* papers by the author in *Trans.* A. S. M. E., vol. xi, On Multiple-cylinder Engines; vol. xv, On Maximum Contemporary Economy of the Steam-engine; vols. xii, xv, On Steam-jackets; vol. xvii, On Superheating.