Future Internal-Combustion Engines—I*

The Physical Processes, Mechanical Methods, Energy Utilizations and Possible Improvements of These Motors

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AN investigation by the United States Department of Agriculture reveals the fact that 68 per cent. of all tractor engine trouble occur in magnetos, spark-plugs and carbureters or in the accessories of the present-day automotive engine. Bearings, cylinders and piston rings, valves and springs, lubrication and starting systems, that is to say, the parts common to all classes of combustion engines, give rise to only 32 per cent. of the troubles. From the point of view of reliability alone we have then a most serious reason to be on the lookout for some new type of automotive engine.

The reason from the point of view of fuel utilization is even more compelling. An engine may be considered as having good carburetion that turns into shaft power more than one-fifth of the fuel energy supplied it. Four-fifths are regularly wasted in our automotive engines. Yet, the fuel must be a peculiarly high-grade one, a liquid meeting severe requirements of volatility, liquidity, etc. The question of continued supply of such a fuel is becoming a serious one. But there are weighty considerations beyond this. In an airplane, fuel has to be carried by engine power. In all aeronautical craft high fuel consumption means a serious reduction in cruising radius. In ocean-going cargo vessels it means a reduction in available revenue space. From purely practical points of view the question of fuel economy, no less than the question of the nature of the fuel, is a momentous one. The question of what a fuel will do for us is wholly a question of what sort of a process the fuel is put through in the engine. What happens to it? Just in what way is combustion turned into power?

It is very unfortunate that in dealing with this question engineers have so far insisted upon being even more abstruse than scientists. The scientists strive to understand what actually goes on. They have by wonderful methods of analysis and experimentation arrived at a point where we feel that we almost see things which, strictly speaking, must remain invisible. We can "see" the individual effects of an electron, a body two thousand times smaller than the smallest atom. We know very accurately the velocities of gas molecules, of which there are a billion billion in a cubic inch; we know how these velocities are distributed. We can see how heat changes into power and power into heat.

In contradistinction to this the engineers persist in dealing with "cycles," an entirely fictitious and artificial something which has no real counterpart in nature, a set of traps really that have got many a very clever inventor into difficulties. To make a high-grade stationary engineer understand the "cycle" operating in his steam turbine, or the inherent "efficiency" of that cycle, one would first have to make him study a textbook of thermodynamics; whereas to show him how the velocities of the steam molecules are converted into the velocity of his turbine blades is a simple thing, requiring hardly any preparation whatsoever.

In this paper the attempt will be made to look at the working processes in internal-combustion engines as processes, not as cycles; although naturally in a paper of the scope of the present one the attempt must remain very sketchy and incomplete.

NATURE OF COMBUSTION AND ENERGY UTILIZATION.

Combustion as usually understood in practice is the more or less violent combination of chemical atoms into new molecules. A number of carbon atoms are tied together with a number of hydrogen atoms to form a hydrocarbon molecule. Two atoms of oxygen are tied together to form a molecule of oxygen. These two molecules arrive in the neighborhood of each other. The attraction between the oxygen atoms on the one side and hydrogen and carbon atoms on the other being extremely strong, the hydrocarbon molecule as well as the oxygen molecule is torn to pieces; the individual atoms rush to each other and molecules of carbon dioxide and water vapor are formed.

The force of the impact of the atoms is such that the new molecules are hurled through space with tremendous velocities. At 3,000°F. the velocity of a carbon dioxide molecule is approximately 3,500 ft. per sec., that of a molecule of water vapor 5,500 ft. per sec. A temperature of 3,000°F. is easily obtained in our internal-combustion engines. The velocity varies with the square root of the temperature. The number of molecules in a cubic inch is, as stated, about one billion billions. Fundamentally our problem is then to utilize for our power purposes the velocities of incredibly small

In this paper the physical processes underlying the conversion of combustion energy into power are discussed and the various methods of producing the pressure differences necessary for the operation of ordinary heat motors. Theoretical and practically attainable energy utilizations of engines and turbines of the compressor, explosion and evaporation types are given and some possible lines of improvement are pointed out. Improvements are found to be possible with all three types. The possibilities of the compressor motor and the steam plant are especially emphasized.

As an illustration of what scientific investigation might bring in the future, certain promising results with electrical combustion batteries are mentioned.—EDITOR.

particles, flying through space with the velocity of projectiles. This problem is complicated by the fact that the velocities occur in all conceivable directions. The molecules shooting through space collide with each other and rebound. Any gas above absolute zero temperature (0° Abs.) may be thought of as a swarm of molecules dashing about in all directions at incredible speeds.

Looking for the moment apart from the electrical utilization of combustion, about which more is said at the end of the paper, two ways of utilizing these velocities present themselves.

In the first place the molecules wherever they dash against a wall exert, by their combined impact, pressure on that wall. This pressure can be easily expressed in figures. It is

$$P = \frac{1}{3} nmv^2, \text{ where}$$

P = the pressure per sq. in.

n = the number of molecules per cu. in.

m = the mass of each individual molecule

v = their speed in in. per sec.

The product nm is the mass of the gas per cubic inch, a quantity well known for all gases.

If the pressure of the gas on the wall is to move the latter, it is manifest that the pressure on the other side of the wall must be lower, so as not to counterbalance the "inside" pressure. The establishment of a pressure difference on two sides of a wall is then necessary to utilize for power purposes the gas pressure exerted by chaotic impacts. On this principle all piston engines, whether reciprocating or rotary, are founded.

A second way out, however, is possible. The velocities of the molecules are chaotic on account of the rebounds in all directions. Suppose the molecules in one certain direction were entirely removed, or at least very much reduced in number. Then those dashing in this direction would not rebound, but would proceed untrammelled on their way. A stream, or jet, in this direction would be established which could be used on a turbine wheel. A gas turbine at once suggests itself. The difficulty here is the high velocities with which the molecules move; then also the high gas temperature incident to combustion. In any case we recognize that removing molecules in one direction means reducing the pressure in this direction. Here again the fundamental problem is the establishment of a pressure difference.

Now as we shall see at the end of the paper, it is possible to establish pressure differences in solutions by chemical means and utilize these pressure differences for the direct production of electricity.

Looking aside from this, however, and confining ourselves to methods more usually recognized as belonging to the field of mechanical engineering, these methods of pressure, or vacuum, production are perfectly well known and not of unlimited number. They are:

- (1) By compressors and exhausters
- (2) By explosions in confined spaces
- (3) By boiling in confined spaces
- (4) By condensation
- (5) By heating and cooling

USING COMPRESSORS AND EXHAUSTERS.

One of the first engines to operate on this principle was that of Brayton. The compressor and the working cylinders of this engine are shown on page 35. A charge of gas and air is drawn into the compressor cylinder, compressed and discharged into a receiver. From there a small amount passes continuously into the working cylinder through the grating a and is kept burning. At the beginning of the working stroke the admission valve b opens and a full charge passes into the working cyl-

inder, igniting as it passes through the flame. The grating prevents the flame from striking back into the receiver. The compressor can be driven from a common crank-shaft or a beam.

Gas and petroleum engines of this type were developed with great energy by Brayton. Two of them were used some time in the seventies to operate a pair of boats on the Hudson River. Yet the grating and other parts gave mechanical trouble. More serious was the fact that the fuel economy was extremely poor. Only 6 per cent of the fuel energy was turned into power. The energy utilization of the Otto explosion engines appearing simultaneously was twice as high. For further progress it becomes necessary for us to look into the nature of energy utilization.

It is commonly known that a pound of fuel can produce a perfectly definite amount of heat or of work on combustion. Engineers mostly assume that the amount of heat and the amount of work are identical and are given by the so-called heating value of the fuel. This heating value is determined by burning the fuel in a bomb calorimeter, either with oxygen or with a substance containing oxygen, like chlorate of potassium. As a matter of fact, the heating value and the maximum work doing capacity are identical only at a temperature of absolute zero. At any other temperature the maximum work doing capacity may be either greater or less than the heating value. At ordinary atmospheric temperature of about 70°F. the conditions are given in Table 1.

TABLE 1. HEATING VALUE WORK DOING CAPACITY AT APPROXIMATELY 70 DEG. FAHR.

Fuel	Ratio Work Capacity to Heating Value	B.t.u. per lb.	Work Capacity hp.-hr. per lb.
Hydrogen burned to water.....	0.94	48,700	19.20
Carbon monoxide to dioxide....	0.98	4,300	1.70
Carbon to carbon dioxide.....	1.00	14,700	5.80
Carbon to carbon monoxide....	1.21	5,390	2.12
Hexane to carbon dioxide and water	1.03	21,400	8.40
Alcohol to carbon dioxide and water	1.03	13,800	5.30

As will be seen the difference between the work and heat values of our two most important fuels, coal and fuel oil, carbon and hexane, is not enough for practical men to bother about. At the same time, that carbon burned to carbon monoxide can be extracting work energy from the atmosphere do 21 per cent more work than that furnished by its heat value, is a fact somewhat too interesting to leave entirely unnoticed even in a paper intended for practical men. We are dealing here with working processes of the future, not knowing even what the fuels will be. It is well to have one's eyes open to all the possibilities of the situation, even if they do not appear to be of any particular interest now.

The Brayton engine turned 6 per cent of the heat or work capacity of the fuel into power. How much could an engine of this type give as a maximum? The working cylinder, before it can give any useful power, must drive the compressor. We must arrive at a ratio between compression and expansion work. When a gas is compressed it means that the molecules are hurled into each other from an advancing wall, their speed increasing with each impact against this wall. The temperature of the gas is inherently nothing else than the velocity energy per molecule, $\frac{1}{2}mv^2$. The gas is heated up. Conversely, when the gas expands the molecules recoil from a receding wall, or a receding mass of molecules and the impacts slow them down. The gas cools. In compression we store up work in molecular energy; in expansion we convert molecular energy into work.

If the terminal temperatures and pressures of a compression and an expansion are the same, then the compression work and the expansion work per pound of gas are the same. If the initial temperature of expansion, measured from absolute zero, is five times the end temperature of compression, then the expansion work between the same pressure limits is five times the compression work. In all our internal-combustion engines by far the main part of the working fluid both before and after combustion is nitrogen from the air. For a rough estimate we can therefore regard the whole engine process as one carried out by compressing, heating and expanding nitrogen alone.

We see immediately that for compressor engines to have a large margin of net power, it is necessary for

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the expansion to be carried out at a much higher temperature range than the compression. The exact figures are:

Ratio of absolute initial expansion temperature to compression and temperature...	2	4	6	8	10
Net work, percentage of expansion work	50.0	75.0	83.0	87.5	90.0

Suppose the compression is carried from atmospheric pressure to about 150 lb. absolute, a compression ratio of 1 to 10. The end temperature of compression from 70°F (1020°Abs.F.) is about 1020°F. absolute or 560°F. We cannot think of handling temperatures in our engines very much in excess of 4000°F. or 4460°Abs.F. The initial temperature of expansion is about four times the end temperature of compression. The net work is then theoretically 75 per cent of the expansion work. To determine the energy utilization we have now only to determine what percentage of the heat put into the gas is converted into expansion work.

Expansion in the ratio of 1 to 10 about halves the absolute temperature. About half the heat is left in the gas. If all the heat came from fuel, we should then theoretically have an energy utilization of $0.50 \times 0.75 = 37.5$ per cent.

Here, however, an extremely interesting possibility of the compressor engine comes into play. As now proposed the combustion in this type of engine is usually

Cross-section of the Brayton engine

Utilizing a heat interchanger in a compressor engine

Combustion chamber and turbine wheel of the Armengaud-Lemale gas turbine

carried out not in the working cylinder but in the receiver. As shown schematically for a gas turbine, the compressor feeds air and a pump supplies fuel continuously to this combustion chamber. An extremely complete combustion of any kind of liquid or gaseous fuel can thus be obtained. Now, suppose we use the exhaust gases to heat the fuel air in a heat interchanger between compressor and receiver. Theoretically speaking the fuel has then only to make up the interval between the exhaust gas temperature and the maximum temperature used. Again, theoretically speaking, since the heat supplied is now exactly equivalent to the expansion work and no heat is lost in exhaust, we have here possibilities of attaining energy utilizations around 70 per cent. A similar possibility does not exist in the case of the ordinary explosion engine, where the exhaust heat is lost at least for purposes of power production in the same engine.

Chart showing effect of injecting water in the combustion chamber upon energy utilization

These possibilities are perfectly well known especially to inventors and investigators in the gas turbine field, and in spite of difficulties occurring in the practical realization of the compressor working process, these possibilities should continue to stimulate to further efforts in the field both of turbines and reciprocating engines. It may be well to point out what the difficulties are. First, the process is peculiarly sensitive to inefficiencies of compressor and expander. If both have an efficiency of 100 per cent then the margin of net work in the example above was found to be 75 per cent of the expansion work.

If the efficiency of the expander is reduced to 60 per cent, leaving 60 per cent of the expansion work available at the shaft and the efficiency of the compressor is also 60 per cent, it then requires $0.25 \div 0.60 = 42$ per cent of the theoretical expansion work to drive it. The margin left is $60 - 42 = 18$ per cent of the expansion work. At 50 per cent efficiency of both expander and compressor the margin disappears entirely. This is something that many investigators, thanks to the obscurity of ordinary mathematical thermodynamics, have failed entirely to realize. It will then not do to operate with any sort of slipshod arrangements. The design must be such as to avoid as carefully as possible friction, throttling and cooling losses. This can, in my opinion, be done to the necessary extent at least in the case of reciprocating engines. In the case of turbines the rotation, or windage, losses in the turbine part and other turbulence losses in the centrifugal compressor part have proved most serious obstacles. All hope is by no means lost yet. If all the money spent in this field by workers with insufficient realization of what the nature of the problem demanded

were spent over again by workers with sufficient scientific insight I think results could be produced.

For compressor engines as well as compressor turbines have run. Such an engine, aside from the Brayton design, is that of Kraus; such a turbine, that of Armengaud-Lemale, the combustion chamber and turbine wheel of which are shown. This outfit was successful enough to lead to the formation of a gas turbine corporation in France. The gas turbines of this company, while they are not used commercially for power production on account of inefficiencies, have been installed regularly to run French torpedoes in connection with stored compressed air. The weight of these turbines is very low, only 1.3 lb. per hp. I have been at work in this field for a long time and once proved to the satisfaction of some leading engineers that combination of a gas turbine with an exhaust-heat steam turbine plant to drive the compressor would be both efficient and at the same time about the cheapest form of stationary plant to build and operate. For reasons that cannot be stated here the development has been held in abeyance.

Second, high temperatures were found necessary to get a good energy utilization. These are serious in a turbine on account of difficulty of cooling the revolving disks and buckets; in a reciprocating engine, on account of the necessity of passing the hot gases through admission valves. However, bucketless turbines may be thought of; disks made of non-metallic materials have recently been talked about in connection with a gas turbine claimed to operate, and valve constructions capable of handling the temperatures without too much cooling and throttling loss should not be beyond the scope of American ingen-

Specific heat curves for fuel at a constant pressure

uity. I have dabbled in the field and am on the whole full of hope. One solution, however, which has often been proposed, that of water injection in the combustion chamber, is fundamentally wrong from the standpoint of energy utilization.

A chart showing the conditions obtaining in this respect is reproduced. This is figured for an actual hydrocarbon fuel, burning with air, not for theoretical conditions. An isothermal compressor efficiency of 0.75 per cent has been assumed. Various expander efficiencies are given on the curve. The full lines give energy utilization without a heat interchanger, the broken dash line the utilization with an interchanger, allowing liberally for heat drop through the walls and allowing no temperatures that steel cannot stand easily. In short, this chart shows what a compressor engine may reasonably be expected to do when running with present-day apparatus on present-day fuel. It will be noticed that utilizations at least nearly equal to those of the Diesel engine may be looked for. The engine needs, however, on high-pressure compressor, has no tricky injection valves, no marvellously high-explosion pressure and yet will run on fuels if anything poorer than those of the Diesel or solid injection engines.

The curves are in thorough accord with such preliminary experiments as have been carried out. It should be noted, however, that water injection may reduce cooling losses to some extent and shift the expander efficiency from a lower curve to a higher. On these conditions, determinable only by experiment, I cannot here enter.

Specific heat curves for a constant volume of fuel

Curves of $C_p \div C_v$ values for various amounts of air

For those who wish to carry out calculations of this kind there are given a set of specific heat values and $C_p \div C_v$ values applicable to the combustion gases from gasoline or kerosene, also crude oil, with varying amounts of air. It is well known that these specific heats increase very considerably with the temperature, rendering calculations with constant specific heats or theoretical thermodynamic formulas based thereon highly inaccurate except for purposes of rough orientation. The curves are based on the most recent determinations by Nernst and others and the exact experimental data are given in another chart.

The indicator diagram of the compressor engine offers nothing of interest. It is a straight compressor diagram for the compression end and a diagram exactly similar to a steam diagram for the expander end.

COMBUSTION IN CONFINED SPACES.

The explosive process as introduced by Otto can be operated either by the compression of the mixture and ignition by special ignition devices, as in all our usual

Experimental data upon which the specific heat curves are based

automotive engines; or by the compression of the air alone and the injection of the fuel at the end of the compression stroke as is done in the Hot-spot, the Hvid and the Brons engines. In the last two mentioned, which are really the same, the ignition is by the heat of compression only. In all these engines only part of the maximum pressure is secured by mechanical compression, the remainder is obtained by temperature increase due to combustion.

This renders the process less sensitive than that of the compressor engine to inefficiencies of compression. On the other hand, since the expansion ratio in an ordinary reciprocating engine can never be greater than the compression ratio, it is manifest that the expansion can never be carried to atmospheric pressure. A great deal of energy is left in the gases in the form of heat. This heat, as stated, cannot be applied advantageously to the working mixture in the same engine. Theoretically, therefore, the working process is less economical than that of the compressor engine with a heat interchanger.

The methods indicated in the previous paragraph have been applied to a process using a compression pressure of 300 lb., absolute, and a maximum temperature of 4,000°F., corresponding to a maximum pressure of 1,060 lb. absolute. The theoretical compression temperature is 800°F., a temperature that may well be expected to preignite any fuel capable of carburetion. The theoretical energy utilization of the engine is 58 per cent. With a compression efficiency of 90 per cent and an expansion efficiency of 80 per cent, the actual utilization of the engine would be 39 per cent. A higher utilization than this should never be expected from any engine using the ordinary explosion process. With fuel injection instead of carburetion higher compressions may be used, but the combustion will be less rapid.

Actually, Diesel engines with compression as high as 550 lb. have in the test stand reached utilizations of over-36 per cent. In these engines, as shown by the diagram, fuel injection by air is arranged so as to maintain a practically constant pressure for a short time interval. From the efficiency point of view this is a drawback. It means that the expansion ratio is less than the compression ratio. At full load or overload the pressure is sustained longer than at reduced load. Hence it is found that Diesel engines at reduced load often give better fuel economies than at full load. This is true until the diagram becomes so "lean" and the expansion work of the gases per stroke so small that it is consumed entirely in the mechanical running losses of the engine.

PISTON ENGINES.

The gain in efficiency due to increased expansion was clearly realized by early gas engine inventors. Charon, Atkinson, McGhee-Burt and others evolved means for obtaining expansion ratios in excess of the compression ratio. Charon on the compression stroke simply rejected part of the charge into the suction line. With a compression giving a mean indicated pressure of only some 43 lb. he attained energy utilization of from 26 to 27 per cent. Similar economies were attained by McGhee-Burt in spite of low mechanical efficiency due to double pistons in two cylinders. Also, Atkinson attained creditable results with his "differential" and "cycle" engines in spite of great mechanical complexity and consequently low mechanical efficiency.

Later on it was recognized that energy utilization could be materially improved by increased expansion due simply to increased compression and the complications of the "prolonged expansion" engines were scouted. However, if the expansion were carried almost to atmosphere with the assumptions used above, an actual energy utilization around 40 per cent might be attained. This is decidedly worth striving for. Americans are strong in the development of ingenious, yet simple, mechanisms. Here is a problem well worthy of a gift of that kind.

For the practical man the two questions of more immediate importance are, however:

- (1) What means have we for making the energy utilization of our ordinary carburetion engines approach the high values just given.
- (2) What are the possibilities of replacing our present type of automotive engines with units of the injection type.

I must admit that I am fundamentally opposed to carbureters and electrical ignition devices. These elements are tricky and complicated laboratory instruments fundamentally differing from the kind of stuff we want to subject to rough handling by amateurs or busy practical men. Our efforts ought to be bent to the abolishment of this type of apparatus.

However, for those of us who nevertheless feel that a bird in the hand is better than ten in the woods, there

are two main ways of attack: (1) The development of fuels allowing lighter compression. Excellent work along this line has been done by Rittman of the Bureau of Mines as well as by the organization headed by Past-president Kettering of this society and probably by others. (2) The perfection of the combustion process. With our present fuels, speeds, carburetion and ignition systems, the combustion in our automotive engines continues all through the expansion stroke, and 20 to 30 per cent of the fuel passes out unburned.

A great deal of very good work is at present being done on carburetion. Some good carbureters even for kerosene seem to be in the process of introduction. Some good scientific research is being carried out. In spite thereof it is not amiss to say that less invention and more scientific scrutiny is the need of the hour. There are close to 4,000 carburetor patents on file in the United States and of these not much over one in

Indicator diagram of a compressor engine

ten is worthy of any notice. We must as a nation come to understand that it is not practical common sense to spend years in trial and tinkering, when 2 weeks of concentrated scientific study might save all that trouble. After all our prodigious efforts it still was necessary for a Government committee during the war to state that we did not know the fundamental principles of the flow of air and liquids through small openings and could not intelligently design a carburetor if we wanted to. Yet all these things are easy to find out.

I have little faith in "fog" mixtures, carburetion by mechanical means only. Such carburetion is apt to be tricky. The best fog, is, however, undoubtedly produced by a liquid that has been in the state of complete evaporation. In this field, however, much better progress would be made if the formation of the fog were studied as a separate problem entirely apart from the engine, rather than by running engines on all kinds of devices and watching for carbon.

Combustion in the engine is accelerated by nothing more than turbulence. In the Gile engine compression takes place between the main piston and an auxiliary one superimposed on it. At the end of the compression stroke the mixture is forced through flutes in the wall into the combustion space. A violent turbulence and a thorough mixing are induced and the engine, according to analysis, gives extremely good combustion; at the expense, however, of a great increase in compression work. The fuel economy, while good, is therefore not suprisingly high. Here is a field for invention. Ignition at several points is a possibility and also a complication.

One point on which there is much misunderstanding among practical men is the question of air heating. Hot air means high end temperature of compression. The maximum temperature producible does, however, not vary much. The ratio of maximum pressure to compression pressure is the same as the ratio of maximum temperature to compression temperature. Hence, with a higher compression temperature we get a lower maximum pressure. The power of the engine goes down. The compression work is a greater percentage of the expansion work and inefficiencies of compression are felt more in the efficiency of the engine. However, if by increasing the temperature of the air we can get a more perfect carburetion and combustion, this as a rule more than offsets the greater influence of compression inefficiencies. Perfect carburetion of present-day kerosene, according to my investigations as published in *Automatic Industries*, Feb. 27, 1919, requires a mixture temperature of about 220°F. and an air temperature before mixing of about 300°F. The temperatures for gasoline, if anybody can say what gasoline is, may be 100°F. for the mixture and 160° for the air.

(To be continued.)