Carnot's Cycle and Efficiency of Heat-Engines.[1]

CARNOT laid down the great and incontrovertible principle that if, when we have obtained motive power by the application of heat, we inquire whether we have obtained the maximum of motive power from this application, we can answer this question by ascertaining whether by applying the same amount of motive power in reversing the process of expansion, or expansion and contraction, in the course of which we have obtained motive power, we can bring the working substance back to its starting-point. When the process is reversible in this manner, we have obtained the maximum possible output in motive power, whatever be the nature of the working substance, gaseous, liquid, or solid.

Carnot thus furnished a criterion by applying which we could judge of the efficiency of a heat-engine. Unfortunately, however, he failed in applying that criterion correctly. His unsuccessful attempt was, however, a great one, since it has continued to mislead scientific men, and confuse engineers, for now more than a century. Carnot invented the famous Carnot cycle, the bugbear of generations of students, and with it an argument to the effect that it is the most efficient cycle possible in the mode of action of a heat-engine.

It is evident that in the cycle described by Carnot, much of the heat taken up from the source in the second stage (isothermal expansion) is thrown away into the condenser in the fourth stage (isothermal compression). This is apparently a waste of heat energy. It is only in the second and third stages of the cycle (namely, isothermal expansion and adiabatic expansion) that work is done on the engine, or motive power is, to quote Carnot's expression, gained. It is, therefore, at the end of stage three that we must apply Carnot's test. When we do so, and simply re-compress the air to its starting volume, we find that much more work has to be done on the air than was done by it during the second and third stages of the cycle. We have, therefore, in stages two and three of the Carnot cycle expended heat which could have been converted more completely into mechanical energy if we had employed adiabatic expansion ; and this waste has evidently occurred in the isothermal stage of expansion, since the third stage is in each case adiabatic.

We thus see that the Carnot cycle is radically inefficient. A great deal of heat is transferred quite uselessly from the source to the condenser, and thus wasted. To obtain from the heat communicated to the air in the cylinder the maximum of work on the engine during the expansion, we must quite evidently make the whole expansion adiabatic, while to reduce to a minimum the corresponding work done by the engine in the compression stage, we must make the whole of the compression isothermal, thus throwing away as much heat as we can with the condenser at its existing temperature.

It is evident that by eliminating altogether the effects of atmospheric pressure, we could at once obtain fifty per cent. efficiency in the cycle of an ideal heat-engine. This is accomplished in the ideal cycle of a steam-engine working with complete adiabatic expansion of the steam down to the pressure of the aqueous vapour in the condenser. In this case the cylinder would be enclosed above, and would contain at the start nothing but aqueous vapour at the pressure corresponding to atmospheric temperature, except for a little water in the space below the piston. In stage 1 the water would be evaporated before the piston was allowed to move. In stage 2 the steam would expand adiabatically, doing work on the engine, until it reached the pressure of the aqueous vapour above the piston. In stage 3 the piston would return to its original position without any net work being done by or on the engine, and the steam not already condensed would condense again to water. Half the heat applied would be spent almost entirely on the engine during expansion, and the other half would pass into the condenser as the piston returned. The efficiency would thus be practically fifty per cent.

We can see now that the percentage efficiency of a heat-engine, or at any rate of a steam-engine, provided that the expansion is adiabatic and complete, and the compression isothermal, does not depend at all on the difference between the initial and final temperature during the expansion. We can quite evidently obtain just the same percentage efficiency with a small as with a great difference of temperature. On this point we are running counter to cherished academic doctrines and to authority which has been generally accepted for more than seventy years ; but that authority rests upon the quite mistaken conclusion that the Carnot cycle is one of maximum efficiency within a given interval of temperature.

Let us now look more carefully, and at the same time from a wider point of view, at the reason why more than fifty per cent. efficiency is impossible in a heat-engine. In the case of the air-engine starting from atmospheric pressure and temperature, it is the atmospheric pressure which limits the stage of expansion. The air can no longer expand and do external work after its pressure has fallen to that of the atmosphere pressing on the upper side of the piston. Now the pressure of the expanding air falls in accordance with Boyle's law in proportion to its relative increase of volume ; but the work done during adiabatic expansion, and consequently the fall in absolute temperature of the expanding gas, depends also on the pressure, and therefore proceeds also in proportion to the relative increase in volume. The air in the cylinder can only exist in the expanded state at the existing pressure in virtue of an increase of absolute temperature proportional to the increased volume. This follows from Charles's law. Hence, assuming Charles's law, for every degree of temperature lost by the air in expansion, the air in the cylinder must be a corresponding degree above the atmospheric temperature which it had before heat was applied to it. When the temperature of the expanding gas has fallen by half the amount to which it had been raised, this condition is no longer possible, and the air can no longer expand against the atmospheric pressure. Half the heat has gone in external work, and half remains in the expanded air, and must be thrown away if the air is to be brought back to its original state with the help of atmospheric pressure alone.

The conception of the Carnot cycle, with its extraordinary peculiarities, was quite evidently based, not on the study of actual heat-engines, but on Carnot's ideas, derived from the caloric theory, of how a heat-engine works. These ideas led him to the conclusion that in the working of a heat-engine, any change of temperature in the working substance, unless the change is accompanied by change in volume, is a waste of heat. Hence the strange feature of the Carnot cycle that in it there is no change of temperature without change of volume.

As we have already seen, the whole of the expansion and none of the compression must be adiabatic

[1] Abstract of a paper on "The Maximum Efficiency of Heat-Engines and the Future of Coal and Steam as Motive Agents," read before the Institution of Mining Engineers on June 16 by Dr. J. S. Haldane, F.R.S.

in a heat-engine working with maximum efficiency. There must also be one and only one stage in which abrupt change of temperature occurs without change of volume. In the steam-engine with maximum expansion of the steam, there is abrupt rise of temperature at the beginning of the cycle. If, as in the Watt-Newcomen engine, there is also abrupt fall of temperature before expansion is complete, loss of efficiency is a necessary result.

At the present time steam-engines and oil-engines are running a neck-to-neck race as regards many employments, while elsewhere the oil-engine is everywhere being applied for quite new purposes, where no heat-engine had previously been applied. In the opinion of many persons the steam-engine is bound to be displaced more and more by the internal-combustion engine. This opinion is largely based on the current academic doctrine that the efficiency of a heat-engine depends on the absolute temperature reached in the engine. In the present paper the academic teaching has been thrown to the winds, backed though it be by the names of men to whom the whole world has good reason to be grateful. A step further may also now be taken. We suggest that the development of the steam-engine has been very greatly hindered by the fallacious teaching associated with Carnot's cycle. Engineers have been prevented from seeing clearly what the maximum efficiency of a heat-engine is, where that efficiency is being needlessly lost, and how the steam-engine can be modified to suit varying circumstances without loss, or with minimum loss, in efficiency.

We still use furnaces and boilers which waste much heat whenever an engine is temporarily out of action or doing only light duty, even though they may be so designed as to cause very little waste, during continuous full duty of the engine. It seems probable that the furnaces and boilers of the future will be gas fed, the gas being formed in a heat-insulated producer or carburettor, and only made and burnt as the steam is required, the whole regulation being mechanical and the heat of the waste gases being nearly all returned to the furnace and boiler. Another alternative presenting similar advantages is the use of pulverised fuel. The boiler and furnace can then be made much smaller than is now usually the case.

As regards modifications of the steam-engine to suit varying circumstances, it seems that small engines, working at very high pressures, and with correspondingly small tubular boilers, will come more and more into use. A steam pressure of 100 atmospheres, with a corresponding temperature of 600° F., seems well within reach. At such a pressure the percentage loss of efficiency, owing to either the discarding of a condenser or condensation at or even somewhat above boiling-point, would not be too large. The bulky apparatus required for complete expansion can thus be dispensed with, reducing the engine to extremely compact proportions and very small weight. By these means the steam-engine can be rendered far more compact and adaptable to varying conditions under which only internal-combustion engines, or steam-engines without a condenser, are now used.

Perhaps too sanguine a view is taken of the future of the steam-engine; but it seems that in every case where either fuel economy or size of engine is of predominating importance, the steam-engine and coal will in the future displace the internal-combustion engine and oil. Even where oil or gas is alone desirable or available as fuel, it will probably turn out to be cheaper, where fuel economy and weight of engine are important, to use them as fuels for steam-engines. The latter will probably take the place of internal-combustion engines in even motor vehicles and aeroplanes. With the further development of electrical transmission of power obtained from coal and steam, the steam-engine and coal will also come more and more to the fore.

The Motion of Whales during Swimming.

By Dr. C. G. JOH. PETERSEN, Director of the Danish Biological Station, Copenhagen.

IN our two well-known Danish zoological handbooks it is stated regarding the swimming of whales, in one that "It is the screwing actions of the hind part of the body (the tail) which force the whale through the water, the tail fin acting only to balance up and down," in the other that "The whales move in the manner of fish by flapping the tail from side to side"; according to a verbal statement, this was observed by the author himself on porpoises in a tank in the Zoological Garden. In the foreign literature I have found information [1] that whales, when swimming rapidly, move the tail fin up and down; when they swim slowly, on the other hand, they perform screw-like motions. Porpoises have been observed in tanks in England to swim by moving the tail fin up and down with slight undulations to each side.

Thus there seem to be greatly divergent opinions as to the manner in which whales effect their swimming movements. I have myself seen dolphins following, *e.g.*, the steamship of the Biological Station, and I have spoken with many others who have seen the same; we are agreed that it is impossible to see how they swim; they only tremble, but follow, apparently with ease, the largest steamship going at full speed.

In the spring of 1924 I was by chance present at a catch of porpoises in the Bramsnæs Vig (by Holbæk), and there I bought the tail of a porpoise just caught. Dr. Blegvad, the assistant of the station, and I dissected it; Fig. 1 is a sketch of the result. At the base the tail fin is very flexible, so long as it is in a fresh condition, similar to the carpus of the hand of man. The vertebræ here are very flexible in relation to each other, and the vertebral column extends right out to the posterior edge of the fin. No muscles are found in the tail fin itself, only four strong tendons extending right out to the extreme vertebræ; these tendons may move the horizontal fin up and down, but scarcely with any force, and doubtfully sideways. The flukes of the tail fin consist only of epidermis and fibrous tissue; they are somewhat elastic for movements up and down. Of other muscles in the tail (hind part of the body), there are two for lateral motions and two for vertical motions; they terminate with strong tendons some distance from the root of the tail fin.

The tail fin with its vertebræ may thus be moved up and down by bending at the root; but these movements do not seem to produce force enough for powerful swimming, because, amongst other reasons, the flukes will impede the speed considerably when in their extreme positions. One can well imagine that quick movements of the flukes towards the horizontal position may give a small speed, as when a rudder is moved in a little boat; this produces a slight speed, if the motions towards the central

[1] Beddard, "A Book of Whales," London, 1900; Murie, "On the Anatomy of a Fin-Whale," Proc. Zool. Soc., 1865; T. Bell Pettigrew, "Animal Locomotion," London, third edition, 1883.