Physics. — *New possibilities for the air engine.* By H. RINIA [1]). (Natuurkundig Laboratorium der N.V. Philips' Gloeilampenfabrieken, Eindhoven — Holland.) (Communicated by Prof. G. HOLST.)

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Introduction.

The main types of caloric engines that have hitherto been found in technical use are summarized in the table below, where they are divided into two groups, viz. *piston engines* and *piston-less engines.* In the first group the potential energy of the expanding working medium is converted direct into energy of the moving parts of the engine, whereas in the second group this conversion takes place via a phase in which the energy is at first present in the form of kinetic energy of the working medium.

A further distinction has been made according to the method of heating.

Summary of the principal types of caloric engines.

Method of heating	Piston engines	Piston-less engines
Internal with oxygen from the air	Internal combustion engines	Gas turbines
Internal without oxygen from the air	Normal fire-arms	Rockets
External, the working medium passing through two phases during the process	Piston steam engines	Steam turbines
External, the working medium remaining in the same phase during the whole process	Air engines	Aerodynamic turbines

The types of engines in the right-hand column are usually more suited for high power, whilst piston engines are for smaller power, and the steam and air engines are also for very small powers.

Several of the types summarized here have only been recently developed,

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[1]) Research in the field of air engines has been undertaken by a group of collaborators of the Philips Physical Laboratory, Eindhoven, under the guidance of the author. This group comprised Ir. H. DE BREY, Ir. F. L. VAN WEENEN, W. H. STIGTER, Ir. W. J. VAN HEECKEREN, the late Ir. Dr. P. H. CLAY, Dr. F. K. DU PRÉ, H.H. METTIVIER MEYER, Dr. B. H. SCHULZ, Ir. A. J. J. LAMBEEK, Ir. A. HOROWITZ, Dr. G. W. RATHENAU. Many others have also contributed by additional research in regard to materials, burners, etc.

because it has not before been technically possible to realize ideas, which often are very old already. In the case of the air engine the position is somewhat different, for this had already reached technical development to a certain extent, but that subsequently came to be discarded. Nevertheless it has for a long time already been realized that the process applied in this type of engine was a very attractive one theoretically. It has now been found that, partly for the same reasons as obtain for the other recent developments, with the present-day technique it is possible to bring the theoretical promises of the air engine to practical realization.

After its invention by STIRLING in 1817 the air engine enjoyed a brief period of success in the middle of the last century, but it failed to stand up against the development of the steam engine and, especially later on, the internal combustion engine.

The principle of the hot-air process.

Fundamentally the air engine comprises two cylinders filled with a gaseous medium, usually air. For the sake of simplicity we will assume that the medium behaves like an ideal gas. The two cylinders are connected together via a regenerator. One has a high temperature T_w, the other a low temperature T_k; further we assume — as is approximately correct — that the temperature of the gas in both cylinders is always the same as that of the cylinder wall.

The volume under the piston in each of the cylinders can be varied from nil to a certain value by moving the pistons. Again assuming ideal conditions, the process brought about by the working medium is as follows:

1st Phase: At the start the volume in the hot cylinder is nil, and that in the cold cylinder at a maximum. The medium in the cold cylinder space is compressed (isothermally) by moving the piston inwards — from now on for the sake of brevity we shall refer to this as the cold piston, while that in the other cylinder will be called the hot piston. The heat of compression thereby developed is carried off. In this phase therefore a certain amount of energy is taken up by the engine.

2nd Phase: Both pistons are moved simultaneously in such a way that the volume of the medium is kept constant, and this motion is continued until the volume of the cold space has been reduced to nil and the gas is consequently all in the hot space (for the sake of simplicity the volume of the connections between the two cylinders and in particular that of the regenerator is disregarded). As a result of the higher temperature prevailing in the hot cylinder the gas there will be under higher pressure. During this phase no external work is performed.

3rd Phase: The hot piston is drawn outwards until the volume equals that of the cold space at the beginning of the first phase. By this motion work is performed which, as a consequence of the higher pressure, is greater than the work done in the first phase. For this (isothermic) expansion heat is required. This heat is applied to the medium externally through the wall of the hot cylinder.

4th Phase: The two cylinders are then again moved in such a way that the total volume of gas remains constant, while the medium is now wholly transferred back to the cold space, thereby completing the cycle. During this phase the external work is again nil.

The net result of the whole cycle is a surplus of energy which is applied by the gas to the pistons. The process described is very difficult to realise. This is approximated in practice by causing the two pistons to move sinusoidally with a certain phase difference. This has to be arranged in such a way that the hot piston in its movement is advanced about 90° in phase in respect to the movement of the cold piston.

The efficiency of the hot-air process.

From the foregoing it is seen that the hot-air process yields mechanical energy. We will now consider what the efficiency is. First of all attention has to be paid to the regenerator. If the cold space and the hot space were connected directly, then during the second phase a considerable quantity of heat would be applied to the gas to heat it from T_k to T_w, and in the fourth phase this heat would be transferred to the cold cylinder. Thus a flow of heat arises, which means a loss. The function of the regenerator, which may consist of a mass of fine wire, is to reduce this loss by accumulating the heat that is contained in the gas when leaving the hot space (4th phase) and giving it off again to the medium as it flows back (2nd phase). Given an ideal action of the regenerator this heat is returned without loss, whilst everywhere in the regenerator the exchange of heat with the gas takes place with an infinitesimal difference in temperature.

The function of the regenerator is of the utmost importance, because the quantities of heat interchanged in it are about three times as large as that which has to be supplied for the actual process. As a matter of fact if there were no regenerator the efficiency would be reduced 4 times.

When the action of the regenerator is ideal and the gas, as already assumed, maintains the temperature T_w in the hot space and T_k in the cold space (so that there too the heat exchange takes place with an infinitesimal difference in temperature) then, with an ideal gas as medium, the process is entirely reversible and the efficiency, according to a known theorem in thermodynamics, is equal to $1 - T_k/T_w$, the same as in a CARNOT process and the theoretical maximum possible with the given temperature ratio. Where the high temperature is 900° K and the low temperature 340° K, the efficiency is therefore 62 %.

In reality compression and expansion do not take place isothermically, because the temperature exchange with the wall is too slow. Consequently the efficiency is reduced, but due to the small compression ratio, i. e. the ratio between the highest and the lowest pressure of the air engine (1 to 2—2.5), this reduction of efficiency does not amount to more than about 10 %, so that on this account and under the conditions given above the efficiency drops to 56 %:

It is also on account of the negligable temperature exchange with the cylinder wall that the heat required for the process is fed to and drawn from the gas in a special heater and cooler respectively, the former being interposed between the hot space and the regenerator and the latter between the regenerator and the cold space.

Differences between the modern and the old constructions of the air engine.

The reasons why full advantage has not hitherto been taken of the theoretical principles of the hot air process were mainly:

a. unfavourable temperature ratio, no suitable heat-resisting alloys being known at that time;

b. unsatisfactory heat transfer, involving voluminous machines with low mechanical efficiency and large heat losses;

c. inadequate regeneration, or even none at all.

It has now been found possible to surmount these difficulties for the greater part. Modern grades of steel allow of the application of a sufficiently high maximum temperature.

Heaters and coolers can now be constructed which in a limited volume and at high speed of the engine perform their functions satisfactorily without involving too large flow resistances. It is essential to limit the volume of this apparatus as much as possible because it forms part of the so-called dead space; this adversely affects the compression ratio and consequently also the output capacity.

It has proved possible to produce regenerators with efficiencies of 95 % and more, which means that they are capable of returning to the gas on its way back 95 and more per cent of the heat given off by the gas on its way to the cold space.

Further, it will be evident that the work performed is proportional to the number of revolutions the engine makes per minute and to the mean pressure of the medium. Both these factors must be high to attain a specific power output corresponding to that of internal combustion engines. At the same time the losses caused by conductance and radiation are low.

Thanks to the improvements described above it has become possible to construct engines which are worked at 3000 revolutions per minute and at a mean pressure of 10 atm. and with an efficiency and an overall output exceeding those of petrol engines of corresponding power.

Finally mention is to be made of a new form of construction for a multi-cylinder engine. It is possible to use four double-acting pistons with mutual phase differences of 90°. The cold bottom end of one cylinder is connected with the hot top end of the next cylinder via a cooler, regenerator and heater, and so on. In this way only one piston per cycle is needed. Mechanically this arrangement is very simple and has a high mechanical efficiency. Moreover it is excellently suitable for combination with a wobbler plate mechanism for converting the rectilineal motion of the pistons into the rotary motion of a shaft. Thanks to the favourable shape of the pressure diagram, which shows no peaks, the difficulties encountered with wobbler plate mechanisms in petrol engines do not arise here.

Characteristic features of the air engine.

In conclusion the main characteristics of the air engine are summarized point for point:

1. The power is in principle proportional to the product of the mean pressure of the working medium and the number of revolutions. It is limited by the amount of heat given off by the heater and cooler; with low number of revolutions a high pressure and a correspondingly high torque, or with high number of revolutions a low pressure and a smaller torque are therefore possible.
   Maximum pressure is limited by the mechanical strength, and maximum number of revolutions by the occurring flow losses.
   It is possible to construct the engine in such a way that the maximum power can be produced over a wide range of speed. This gives the engine a characteristic analogous to that of a series wound electric-motor, which is of great importance for traction. The minimum number of revolutions is only limited by the piston leakage and is very low.
2. The torque is controlled by varying the mean pressure of the medium (in fact by varying the quantity of the medium). As the heater is kept at the same temperature the thermal efficiency does not vary with the load.
3. The engine is noiseless, there being no valves and no exhaust noise.
4. As heating is applied externally no special requirements are made of the fuel.
5. The favourable pressure diagram results in a uniform torque (in a 4-cylinder engine the variation is only about 8 %).
6. There is very little wear, as there are no hot running surfaces and neither dust nor corrosive gases inside the cylinder.
7. For the same reasons as under 6. the lubricating oil consumption is very low.
8. It is possible to burn the fuel completely, so that there is no CO in the exhaust gas.
9. Starting (at room temperature) takes more time than is the case with combustion engines, because the heater has first to be warmed

up, but once hot, the starting is most reliable and independent of the surrounding temperature.

10. Cooling requirements are higher than for internal combustion engines, because as the cooling temperature rises the efficiency drops. The amount of heat given off is about the same as that with an internal combustion engine.
11. In the multi-cylinder construction the direction of rotation can be reversed while running by reversing the order in which the cold and hot spaces of the successive cylinders are connected.

Hot-air process applied to refrigeration.

As already mentioned, the hot-air process, in principle at least, is reversible. This means that it can be applied in such a way that a certain amount of heat is drawn from a low temperature reservoir and, while simultaneously applying external work, imparted to a high temperature reservoir.

In this reversed process the same high thermodynamic efficiency is attained. By giving the right form to the elements corresponding to the heater, regenerator and cooler it has been possible to make efficient refrigerators. An experimental test with hydrogen as working medium showed that a temperature of 80° K could be reached in one stage. This process is in fact excellently suitable for cooling to temperatures which are not easily attainable by the usual methods.