THE GAS TURBINE

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In view of the rapid development of the steam-turbine and of the great advantages it possesses over the reciprocating engine in the matter of efficiency, smoothness of operation, and output per unit weight, the possibility of combining these mechanical advantages with the high thermal-efficiency of the internal-combustion engine by means of the internal combustion turbine is an extremely attractive proposition. Numerous attempts have been made to produce an efficient and reliable internal-combustion turbine, but the difficulties standing in the way of such an achievement are formidable. The purpose of this Paper is to give a brief account of the most noteworthy of these attempts, together with a summary of the results obtained and an indication of possible future developments.

It is not proposed here to consider the theoretical aspect of the gas-turbine, but it may be stated in passing that the same working cycles may be used as for the reciprocating engine. These cycles fall naturally into two classes:—

(*a*) Constant-pressure cycles, as exemplified in the Diesel engine and the Armenguad and Lemale turbine.

(*b*) Constant-volume cycles, as exemplified in the Otto gas-engine and the Holzwarth turbine.

There is one difference which should be noted between these cycles as employed in the reciprocating engine and in the turbine respectively; in the former, compression is approximately adiabatic, while in the latter it is as nearly as possible isothermal in order to reduce the negative work required.

CONSTANT-PRESSURE TYPE TURBINES

The Work of Armengaud and Lemale. In 1906 M. René Armengaud constructed two constant-pressure type turbines. A 25 h.p. de Laval turbine was altered so as to operate with compressed air. Air was supplied from a high-speed compressor of known efficiency to the combustion chamber, together with measured quantities of gasoline vapour. The mixture was ignited by means of an incandescent platinum wire, and combustion took place at a constant pressure of about ten atmospheres, the flame temperature being 1,800°C. The combustion chamber was lined with carborundum. A steam-coil was placed in this chamber, steam mixing with the products of combustion and passing out at a temperature of 400°C. The mixture then passed through a de Laval nozzle losing heat and gaining kinetic energy, and impinged on a wheel in the usual way. The power required to drive the compressor was about equal to half that obtained from the turbine alone, the net output being 30 h.p.

A larger machine was also built operating on the same principle, but differing somewhat in constructional details. The first part of the combustion chamber was lined with carborundum backed by sand; the second part was surrounded by a coil circulating water, which then passed round the jet nozzle discharging into the passage leading to the jet and was there converted into steam by the hot gases. The nozzle then converted all the energy into motion, so that the temperature to which the vanes were exposed was reduced to a minimum. The wheel had water-passages for cooling, and each vane had a hollow into which water found its way. The compressor was mounted directly on the turbine spindle, and was of the Rateau Type, being really an inverted four-stage turbine, having an efficiency of 65 per cent. The turbine speed was 4,000 r.p.m. and the output 300 h.p. The fuel consumption amounted to 3·9 lb. of petrol per b.h.p. hour.

The Conninck Turbine.—A new type of gas-turbine has recently been devised by M. Conninck. The cycle of operations is as follows: A certain quantity of fuel is burned in a stream of air in a combustion chamber at constant pressure, producing a pressure of 450 lb. per square inch and a temperature of 800°C. The gases are expanded to 220 lb. per square inch, at 550°C., doing work on the moving turbine vanes, and are then passed to a second combustion chamber where a further supply of fuel is admitted, raising the temperature again to 800°C. at a constant pressure of 220 lb. per square inch. Further expansion to 30 lb. per square inch at 550°C. follows, and the gases pass to a third combustion chamber where a further supply of fuel raises the temperature to 1,000°C. The third expansion is split up into three stages—30 lb. per square inch to 0·5 atmosphere, 0·5 to 0·25 atmosphere and 0·25 to 0·125 atmosphere—with a final temperature of 340°C. Compared with the theoretical curves, practice shews a gain of entropy due to turbulence and internal friction.

The gases are cooled at constant pressure from 340°C. to 250°C. To bring the gases back to atmospheric pressure four compression stages are used, two stages with a pressure ratio of 2 : 1 and a total temperature rise of 175°C. and two stages with a ratio of $\sqrt{2}$: 1 and a total temperature rise of 75°C.

The system of splitting up the combustion into a number of stages reduces the maximum temperature to which the blades are exposed, but at the same time the thermal efficiency is correspondingly reduced. It is understood that M. Conninck has constructed a machine of this nature, but no test results are available.

CONSTANT-VOLUME TYPE TURBINE.

The constant volume, or explosion type of turbine, has theoretically a higher efficiency than the constant pressure type operating on a corresponding cycle, and has been developed in Germany by Holzwarth to a greater extent than any other type of internal-combustion turbine. Holzwarth states that intermittent (that is, explosive) action is necessary for two reasons:—

(*a*) Proper combustion and pressure development can only be obtained in a closed chamber, and

(*b*) Satisfactory cooling is impossible with continuous combustion.

Holzwarth's First Turbine.—Holzwarth's first gas-turbine, constructed at Mannheim in 1910, had a vertical shaft with the dynamo mounted above the turbine. Ten combustion chambers were cast in the base of the machine. The lower part of each chamber carried gas and air inlet valves, and an ingenious form of nozzle-valve was placed at the top of each chamber. The rotary element was a two-stage Curtis wheel about 1 metre in diameter. The combustion chambers were fed with a mixture of gas and air at a pressure of about two atmospheres, compression being effected by means of rotary compressors which were operated by steam raised by waste heat from the exhaust gases. Ignition was effected in the chambers in series by means of a Bosch high-tension magneto, the sudden rise of pressure forcing open the nozzle-valve and allowing the gases to impinge on the wheel. As the pressure in the combustion chamber fell, the nozzle-valve gradually closed, but the action was delayed until a certain quantity of compressed air alone was passed through the chamber for scavenging and cooling purposes. When the nozzle-valve was closed air and gas were readmitted, the inlet valves closed, the spark was passed and the cycle repeated.

Many practical difficulties were encountered. Various fuels were burned with greater or less success—power gas from anthracite, light and heavy benzine, petroleum, gas oil, benzol and tar oil, and lighting gas. Attempts to burn coal-dust ended in failure, and eventually the best results were obtained with producer-gas derived from coke, with an interrupted fuel injection to " laminate " the gas and air change. Trouble was experienced due to unstable combustion (that is, detonation), and was overcome by using cooler air and better scavenging, and by water-cooling the combustion chambers.

The machine was rated at 1,000 h.p. but with ten chambers in use only 160 h.p. could be obtained. When only four chambers were in use an output of 136 h.p. was obtained, which would seem to indicate interference between the action of the chambers.

Development of the Holzwarth Gas Turbine since 1914.—In 1914, a few months before the outbreak of war, tests were started on a 1,000 h.p. vertical gas-turbine by Thyssen and Co. of Mulheim, Ruhr. The tests were discontinued during the war, but were resumed in 1918. This machine bears a general resemblance to the earlier Mannheim one, but differs from it in several particulars of design:

(*a*) Higher charge pressures and explosion pressures were adopted to increase the output and thermal efficiency. The average explosion pressure is now 170–200 lb. per square inch, compared with 70–85 lb. per square inch in the Mannheim turbine. According to some curves published by Holzwarth in the " Zeits. des V.D.I. " 28th February 1920, this increase in pressure corresponds to a theoretical increase of efficiency from 26 per cent. to 41 per cent.

(*b*) The period of expansion was reduced. This reduces the heat loss to chamber and nozzle walls, and increases the kinetic energy and efficiency.

(*c*) Changes were made in the blades and fastenings. The shorter period of expansion causes a greater pressure on the blades, the sudden intermittent action resembling a blow. Curtiss blades proved unsuitable for these conditions and a new form of blade was devised. The blade is cut from the solid and carries a welded cap at the outer end, butting up against the caps of adjacent blades and so forming an outer stiffening ring. The root of the blade is machined to a corrugated form and has a tapered radial slot cut in it, into which a corresponding tapered key is driven, thus forcing open the root and maintaining a constant stress between the blade and the wheel. A soft electric iron was chosen as the most suitable material.

(*d*) Various nozzle shapes were tried, with results corresponding fairly closely to those obtained in steam practice; a de Laval nozzle with the smallest possible angle at exit proved the most satisfactory.

After prolonged experiment Holzwarth has decided that the horizontal shaft machine is preferable to the vertical machine, and in future all machines are to be of the horizontal type.

In addition to the 1,000-h.p. vertical turbine already mentioned it appears that a horizontal machine of 5,000 kw. has been supplied to the Muldenstein power-station (Saxony). The Prussian State Railway administration has taken great interest in the development of the gas-turbine, and in 1919 orders were placed for a 3300-kw. gas-turbine plant and for a 500-h.p. oil-turbine driving a d.c. generator. A similar oil-turbine for marine work was completed in December 1920, the d.c. generator being in this case replaced by a mechanical reduction-gear.

This machine has a horizontal shaft, and six equally spaced combustion chambers, each of 150 litres capacity, arranged round the shaft. The principle is between that of a gas-engine and that of a Diesel engine. The fuel is injected through an atomizing valve into the longitudinal combustion chamber. A separate compressor is used driven by a small steam-turbine for which steam is raised by heat from the exhaust gases. The compression is considerably lower than in the gas-turbine, and is insufficient to ignite the charge, for which purpose a spark is used. As a consequence only the more volatile oils like petrol and paraffin can be used, and the thermal efficiency is also reduced. The actual explosion pressure is about 205 lb. per square inch. The mean temperature in the combustion-chambers is 470–550°C and of the exhaust 430–470°C. Only 9 per cent. of the heat of combustion is lost in the cooling water. There are from 50–60 cycles per minute per chamber. This machine exhausts against a back pressure of 2 or 3 lb. per square inch and runs at 3,000 r.p.m. A 500-kw. oil-turbine coupled to a generator and exhausting to a waste-heat boiler was illustrated in "The Motorship," May 1922.

Effect of Temperature before Ignition on Explosion Pressure.—Unless the temperature before ignition is kept within fairly close limits, detonation is likely to occur. No extra work is obtained thereby, the heat evolved being precisely the same as with quiet burning. There is a sudden rise of pressure and temperature, producing big stresses and resulting in loss through shock and low nozzle efficiency. With carbon monoxide the following results were obtained:—

Initial temperature – –	100°C	200°C	400°C
Pressure from quiet burning/initial press – – –	7·7	6	4·3
Detonation pressure/initial press – – – –	8·1	14	5·7

Governing.—Little difficulty has been experienced in governing explosion turbines. It may be effected either by varying the number of nozzles in use or the number of explosions per minute.

Apart from the work of Holzwarth very little has been done with the explosion turbine. In America one turbine rated at 200 h.p. was built in 1916, and another rated at 100 h.p. in 1917. It does not appear that any success has been achieved with either of these machines.

COMPRESSION AND REGENERATION.

One of the most vital features of any internal-combustion engine is the compression of the charge. This is done in a reciprocating engine directly by the piston on its return stroke, and the efficiency of this operation is about 98·5 per cent. In the case of a turbine a rotary compressor is essential on account of the large volume of air to be dealt with, and also for mechanical reasons. Unfortunately, the efficiency of the rotary compressor is low, being only about 70 per cent. under favourable conditions. Further, to obtain a satisfactory compression it is necessary to employ a large number of stages. It has been proposed to use a rotary compressor for the L.P. stages, discharging to a piston compressor for the H.P. stages; it is rather doubtful whether the gain of efficiency so obtained would outweigh the additional mechanical complications.

Methods of Driving Compressor.—(*a*) The compressor may be mounted on the turbine shaft. Since the turbine efficiency is only about 55 per cent. and the compressor efficiency 70 per cent., this is a very inefficient method; further, it cannot meet the conditions of starting up or altering the rotational speed of the main turbine.

(*b*) The heat in the exhaust gases may be used to generate steam which operates a separate steam-turbine driven compressor. This is the most satisfactory system, and is used in the Holzwarth turbine. This system involves the principle of regeneration, to which brief consideration may here be given.

Regeneration.—Only a small proportion of the heat of combustion is recovered directly as mechanical work; a further proportion must be recovered as sensible heat. The heat contained in the exhaust gases may be transferred from them by means of a regenerator to the compressed air on its way from the compressor to the combustion chamber. With gaseous fuel, a regenerator may also be used for preheating the gas. The generator may consist of a series of iron tubes like those of a surface condenser, or of stoves like those used with blast furnaces, or of a combination of the two, and may have a transmission efficiency as high as 75 per cent. Another type of regenerator consists of a tubular boiler for generating steam from the heat of the exhaust gases, this steam being used in an independent steam turbine as already described.

The power available for external work may be about doubled by the use of a regenerator, whether it is for gas to gas or gas to water. The efficiency of the regenerating plant is, therefore, of great importance. Regeneration by heating the air and gas supply is more efficient than by steam raising, but is liable to result in temperatures which are above the working limits of the materials used. On this account steam regeneration is generally preferred and is the only system that has been applied to the explosion turbine.

MATERIALS OF CONSTRUCTION.

Great difficulty has been experienced in finding materials which will stand up to the very severe conditions of service inevitable in a gas-turbine. Many steels, hard and soft, alloyed and unalloyed, were tried as blading material, without success. Eventually a soft electrolytic iron suitably heat treated was found capable of resisting wear and chemical action, provided that there is no appreciable amount of water or wet steam present in the gases. The physical properties of this material are as follows:—

	15°C.	450°C.
Yield-point—Tons per sq. in. - -	26·7 max. 20·2 min.	12·54
Maximum strength—Tons per sq. in. -	28·6	16·95
Elongation—Per cent. - - - -	27·2	50·2
Contraction—Per cent. - - - -	73·0	88·4

This material is stated to have given satisfactory results in the Holzwarth oil-turbine previously referred to.

Pure wrought-iron blades have given satisfactory service in steam-turbines, but, in these, temperatures of 450°C have not been exceeded. For use in a gas-turbine the material must be capable of withstanding 600°C and over. Nickel is too expensive and brittle, but copper-nickel alloys have given promising results. The following table summarizes the results of some research on gas-turbine materials which were published in the Mattalborse, 13th March 1920.

Temp.	Chemical Composition.	Strength.	Ductility.	Remarks.
°C.	Per Cent.	Tons per sq. in.	Per Cent.	
600	Ni 100	12·72	16	Expensive. Very brittle at 300–350°C.
580	Cu 80 Ni 20	12·10	15·5	Very readily attacked. Better results with Cu 60 per cent., Ni 40 per cent., and also with Cu 27–35 per cent., and Ni 73–65 per cent.
515	Cu 55, Ni 21, Zn 24 (Argentan)	12·72	41	—
650		6·62	40	
600	Ni 6, Cr 20, Co 6 (Chrome Nickel Steel)	29·90	19	Elastic limit 10·2 tons. Remained free from scale in an air bath.
700		15·30	7	

The chrome-nickel steel with an iron content of 74 per cent. is the most satisfactory, and may be employed at 700°C.

The well-known "Stainless steel," containing 12–13 per cent. of chromium, suggests itself as a possible blading material for the gas-turbine. Its mechanical properties at high temperatures are inferior to those of the chrome-nickel-cobalt steel previously referred to. Moneypenny gives the tensile strength at 600°C and 700°C as 24·2 and 12·1 tons per square inch respectively, as against the figures of 29·9 and 15·3 tons per square inch with the chrome-nickel-cobalt steel. The so-called stainless steel is also very readily attacked by hydrochloric and sulphuric acids, and when a fuel is used containing a certain amount of water and traces of sulphur, sulphuric acid is formed, resulting in rapid corrosion. Severe troubles from this cause were experienced by Armengaud and Lemale on account of the injection of steam into burning gases. The Holzwarth turbine is fairly immune from this trouble since no water or steam is mixed with the gases.

The best alloys for acid resistance are those of Cobalt, one of the most successful being Cu 52 per cent., Co. 25 per cent., Zn. 23 per cent.

Very much more extended research will be necessary before it can definitely be said that a satisfactory blading material has been found. In addition to possessing the necessary physical properties at high temperatures the material must also be reasonably cheap to manufacture and must be capable of being machined and worked. It appears that metallurgists are within measurable distance of producing a material which will stand up to a temperature of 600°C.; any increase of the working temperature above this figure renders the metallurgical problem very much more difficult.

RESULTS OBTAINED.

The Holzwarth turbine is the only gas-turbine for which claims of commercial operation have been made. According to Professor Schule, writing in the *Electrotechnische Zeitschrift* for 21st and 28th July 1921, the Holzwarth turbine fulfils the main requirements of an internal-combustion engine. Within the limits imposed by practical considerations it is theoretically capable of giving a thermal efficiency of 40 per cent. Professor Schule states that tests on a 1,000 kw. set showed an overload capacity of 20 per cent. at the periphery, the difficulty now being to transmit the power to the shaft without serious windage and friction losses. He further states that in May 1921 the Holzwarth turbine had given results economically comparable with those of the steam-turbine.

The following figures relate to tests made on a 1,000 h.p. Holzwarth turbine at Mulheim (Ruhr) in December 1919, using gas having a calorific value of 430 B.Th.U. per lb:—

No. of explosion chambers	10
Capacity of explosion chambers	8·12 cu. ft.
Mean charge pressure	2·1 atmos.
Max. explosion pressure (average value)	11·0 ,,
Exhaust pressure	1·06 ,,
Peripheral velocity of wheel	515 ft. per sec.
No. of stages	2
Temperature in explosion chamber	415°C.

Test No.	1.	2.	3.	4.
Power output at wheel periphery — h.p.	70	251	724	984
Heat consumption B.Th.U./h.p.-hr.	—	24,160	11,580	9,720
Peripheral efficiency per cent.	3·9	10·4	21·8	26·0

It is impossible to discover from this data what is the actual efficiency of the turbine. As a result of discussion and correspondence between Stodola and Holzwarth it appears that the actual overall efficiency of the machine is 13 per cent. With large units it should be possible to realize an overall efficiency of 25 per cent.

Thus the best result anticipated with the Holzwarth turbine in large sizes is just about equivalent to the best results obtained in steam-turbine practice.

The gas-turbine must be regarded as a possible competitor to the steam-turbine rather than to the internal-combustion engine. In order to achieve any degree of commercial success the internal-combustion turbine must fulfil the following conditions:—

(*a*) The capital cost must be low.

(*b*) The thermal efficiency must be at least as high as in the best steam-turbine practice.

(*c*) The fuel used must be cheap.

(*d*) The degree of reliability and the maintenance charges must compare not unfavourably with the corresponding figures for steam plant.

With regard to (*a*), (*b*) and (*c*), from the remarks made in the preceding section it is apparent that the gas-turbine may be expected to show little, if any, saving in fuel, a large saving in capital costs, and a considerable economy by the recovery of valuable by-products. The importance of this recovery of by-products is likely to increase as time goes on. With the oil-turbine this advantage does not apply, and apart from this the oil-turbine is completely out of court until it can operate on crude heavy oils.

With regard to reliability and maintenance charges, it is obvious that the Holzwarth turbine is very much more complicated than the steam-turbine. On this account, as well as on account of the much higher working temperatures experienced, the Holzwarth turbine is likely to prove far less reliable in operation than the steam-turbine. The importance of reliability and immunity from breakdown, more especially in the case of large units, cannot be over-estimated, and the gas turbine is not likely to make much headway until its reliability has been demonstrated.

The two chief obstacles to the development of the gas-turbine are the limitation of working temperature imposed by the materials used and the inefficiency of the rotary compressor. Of these, the former will doubtless be overcome sooner or later by metallurgists. The rotary compressor, on the other hand, has not improved materially in efficiency during the last fifteen years in spite of much thought and experiment that have been devoted to the matter. If a satisfactory compressor could be devised the problem of the gas-turbine would be tremendously simplified.

It may be said that the gas-turbine has not yet become a commercial proposition, nor is there any immediate prospect of its doing so. The progress that has already been made, however, is sufficient to indicate that it is possible that engineering progress will ultimately overcome the obstacles which at present prevent such development.