THE COMPOUND STEAM TURBINE AND ITS THEORY, AS APPLIED TO THE WORKING OF DYNAMO-ELECTRIC MACHINES

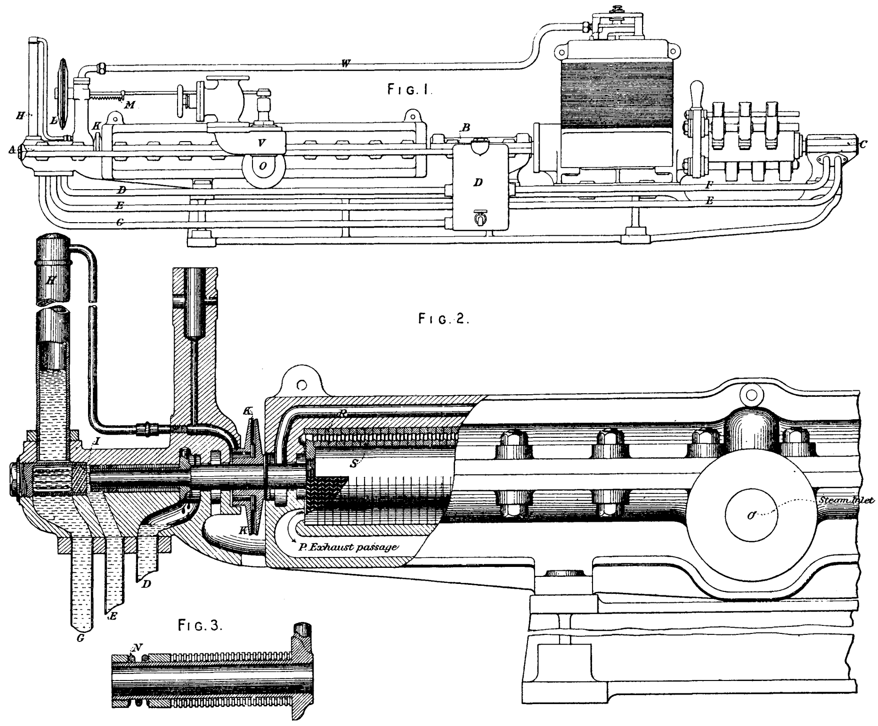
North-East Coast Institution, December 19th, 1887

[The paper opens with a short discussion of the principles of water turbines. That part is omitted here.]

The essential conditions for high efficiency are, as we have said, absence of shock and low residual velocity. These conditions, in the case of the water turbine, can be better obtained in the types called the outward or inward flow than in the parallel flow, for the large volume of water to be dealt with necessitates long blades of double curvature for the last-mentioned type, these are objectionable, while it is more difficult to minimise the residual velocity of the water leaving the wheel. Principally these reasons have led to the more general adoption of the outward or inward flow types than of the parallel flow. After careful consideration, however, the parallel flow type seemed more suitable to the compound steam turbine, and has been accordingly adopted.

Fig. 2 shows the arrangement of ninety complete turbines, forty-five lying on each side of the central steam inlet. The guide blades R are cut on the internal periphery of brass rings, which are afterwards cut in halves and held in the top and bottom halves of the cylinder by feathers; the moving blades S are cut on the periphery of brass rings, which are afterwards threaded and feathered on the steel shaft, and retained there by the end rings which form nuts screwed on to the spindle. The whole of this spindle with its rings rotate together in bearings, shown in enlarged section (Fig. 3). Steam entering at the pipe O flows all round the spindle and passes along right and left, first through the guide blades R, by which it is thrown on to the moving blades S, then back on to the next guide blades, and so on through the whole series on each hand, and escapes by the passages P at each end of the cylinder connected to the exhaust pipe at the back of the cylinder. The bearings (Fig. 3) consist of a brass bush, on which is threaded an arrangement of washers, each successive washer alternately fitting on to the bush, and the block, while being alternately 1/32nd smaller than the block outside, and 1/32nd larger than the bush in the hole. One broad washer at the end holds the bearings central. These washers are pressed together by the spiral spring N and nut, and by friction against each other, steady or damp any vibration in the spindle that may be set up by want of balance or other cause at the high rate of speed that is necessary for economical working.

The bearings are oiled by a small screw propeller *I* attached to the shaft. The oil in the drain pipes *D* and *F*, and the oil tank *D* lies at a lower level than the screw, but the suction of the fan *K* raises it up into the stand pipe *H* over and around the screw, which grips it and circulates it along the



Figs. 1, 2 and 3

pipes to the bearings. The course of the oil is as follows: The oil is forced by the propeller *I* and oils the bearing *A*, the greater part passes along the pipe *E* to the end bearing *C*, some, after oiling the bearing *C*, drains back by the pipe *F* to the reservoir *D*, the remaining oil passes along the armature spindle, oils the bearings *B*, and drains into the reservoir *D*, from which the oil is again drawn along the pipe *G* into the stand pipe *H* by the suction of the fan *K*. The suction of the fan is also connected to the diaphragm *L* and forms, with it and the spring *M* the principal part of the governor which actuates the throttle valve *V*. Fig. 4 is the electrical control governor, which will be further described in connection with the dynamo. It acts directly upon the controlling diaphragm *L* by admitting or closing a large access of air to it, and thus exercises a controlling influence upon it.

For small differences of pressure the velocity of air or steam passing orifices or short tubes is given by the same formula as that for water. The heads of pressure have to be calculated in each case in terms of the respective fluids, and for small differences of pressure the velocity of efflux is the same for the same head in all cases. This has been recognised as a fundamental principle; it has also been verified in some of the cases we are going to consider by actual measurements.

We now proceed to consider the action and condition of the steam as it passes through the successive turbines, but, before doing so, it will be necessary to go into some calculation in order to form a correct basis to start from.

The velocity of efflux of steam flowing from a vessel at 15·6 lb. per square inch absolute pressure through an orifice into one at 15 lb. absolute pressure is 366 feet per second, the drop of pressure of 0·6 lb. corresponding to a diminution of volume of 4 per cent. in the opposite direction. We must now suppose that the turbines are so proportioned and the blades so diminished in size that each one nearer the steam inlet, *O*, has 4 per cent. less blade area or capacity than the preceding one all the way from each of the exhaust ends up to the centre.

If we work this out we find that after forty-five turbines the pressure will be about 69 lb. above the atmosphere of the inlet. The steam will have followed some curve of temperature and volume very near the adiabatic but on the isothermal side of it; the velocity of flow will be slightly greater near the inlet in consequence of the increased temperature. The steam enters from the steam pipe at 69 lb. pressure and passes through the first turbine, consisting of a ring of guide blades and then a ring of moving blades, and falls 2·65 lb. in pressure; the velocity due to this fall in pressure is 386 feet per second; its volume increases by 3·85 per cent. of its original volume; it passes the second turbine, falls 2·55 lb., and again increases its volume in the same ratio, and so on till it reaches the last turbine, where its pressure is 15·6 lb. before entering and 15·0 lb. on leaving it to flow into the exhaust pipe. The velocity due to the last drop is 366 feet per second. The steam has therefore nearly the same velocity of flow for all the turbines; in other words, the error in assuming the velocity due to the head to be 376 feet per second throughout does not exceed 3 per cent. The velocity of the wheels at 9200 revolutions per minute is 150 feet per second, or 39·9 per cent., of the mean velocity due to the head throughout the turbines.

On comparing this ratio of velocity of wheel to velocity of flow with that of the Tremont water turbine we find a corresponding efficiency of a little over 72 per cent. Hence in the compound turbine we are describing, the velocity of the blades is sufficient to secure a very high return of useful effect. We may, therefore, assume that if the blades be equally well shaped in the steam turbine as in the water turbine, and that the clearances be kept small and the steam be dry, then each turbine of the set will give an efficiency of at least 72·5 per cent. We say "at least" because as each turbine discharges without check into the next, the residual energy after leaving the moving blades is not lost as it is in the case of the water turbine we are considering (it amounts to from 3 to 5 per cent. of the energy), but continues into the next guide blades, and is wholly utilised there in assisting the flow. This unchecked flow from one turbine to another is a great advantage of the parallel flow type over other types where a number of turbines are compounded. It also minimises the skin friction, as nearly the whole of the moving part is covered with blades, and there is consequently no appreciable loss due to this cause.

As each turbine of the set gives 72·5 per cent. efficiency it follows that, as the steam at all points expands gradually without shock, the motor as a whole will give an efficiency of at least 72 per cent. of the total mechanical energy of the steam, or in other words, over 72 per cent. of the power derived from using the steam in a perfect engine, without losses due to condensation, clearances, or friction, and such like. A perfect engine working with 90 lb. boiler pressure, and exhausting into the atmosphere, would consume 20·5 lb. of steam per hour for each horse-power; a motor giving 70 per cent. efficiency would therefore require 29·29 lb. of steam per horse-power per hour.

We have now gone sufficiently into the question to show clearly that in the compound steam turbine we have a motor whose theoretical efficiency is very high indeed. The fact that at each turbine of the set the temperature is constant, enables us to predict that there can only be a very minute loss arising from condensation. This has been conclusively verified by experiments with superheated steam, coupled also with the fact that "for small differences of pressure gases and vapours act like liquids in flowing through orifices and tubes, in virtue of the small differences of pressure, and that the velocity of flow is regulated by the fundamental formula $v = 8\sqrt{n}$". These three facts draw the analogy between the water turbine and the compound steam turbine for efficient working as close as it is possible to draw anything, and it does not seem too much to expect, in the larger sizes at any rate, an equally good efficiency.

The dynamo which forms the other portion of the electric generator (Fig. 1) is coupled to the motor spindle by a square tube coupling fitted on to the square spindle ends. The armature is of the drum type, the body is built up of thin iron discs threaded on to the spindle and insulated from each other by tracing-paper. This iron body is turned up and grooves milled out to receive the conducting wires. For pressures of 60 to 80 volts there are fifteen convolutions of wire, or thirty grooves.

The wire starting at b is led a quarter of a turn spirally, c, round the cylindrical portion a, then passing along a groove longitudinally is again led a quarter turn spirally, d, round the cylindrical portion a, then through the end washer and back similarly a quarter turn over e, then led along the diametrically opposite groove, and lastly, a little over a quarter turn f, back to g, where it is coupled to the next convolution (Fig. 5).

The commutator is formed of rings of sections; each section is formed of short lengths; each length is dovetailed and interlocked between conical steel rings; the whole is insulated with asbestos, and when screwed up by the end nut forms with the steel bush a compact whole. There are fifteen

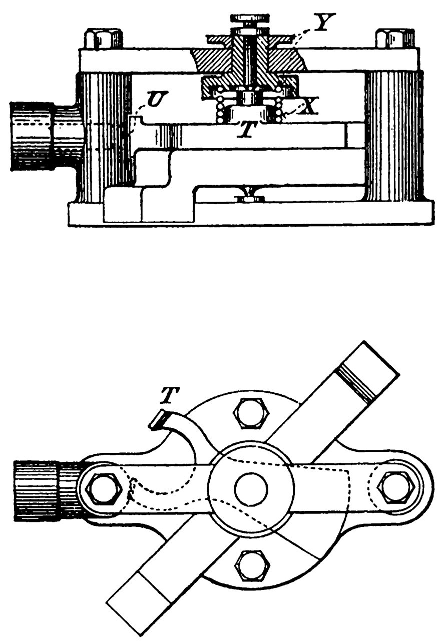


Fig. 4

sections in the commutator, and each coupling is connected to a section. The whole armature is bound externally from end to end with brass or pianoforte steel wire. The magnets are of soft cast iron and of the horse-shoe type; they are shunt wound only.

On the top of the magnet yoke is the electrical control governor (Fig. 4). It consists of one moving spindle on which are keyed a small soft iron bar, and also a double finger T. There is also a spiral spring X attached at one end to the spindle, and at the other to an adjustable top head and clamping nut Y.

The double finger T covers or opens a small hole in the face U, communicating by the pipe W to the diaphragm L.

The action of the magnet yoke is to attract the needle towards the poles of that magnet, while, by turning the head, the spiral spring X is brought into tension to resist and balance this force, and can be set and adjusted to any degree of tension. The double finger T turns with the needle, and by more or less covering the small air-inlet hole U, it regulates the access of air to the regulating diaphragm L. The second finger is for safety in case the brushes get thrown off, or the magnet circuit be broken, in which case the machine would otherwise gain a considerable increase of speed before the diaphragm would act. In these cases, however, the needle ceases to be attracted, falls back, and the safety finger closes the air-inlet hole.

There is no resistance to the free movement of this regulator. A fraction of a volt increase or decrease of potential produces a considerable movement of the finger, sufficient to govern the steam pressure, and in ordinary work it is found possible to maintain the potential within one volt of the

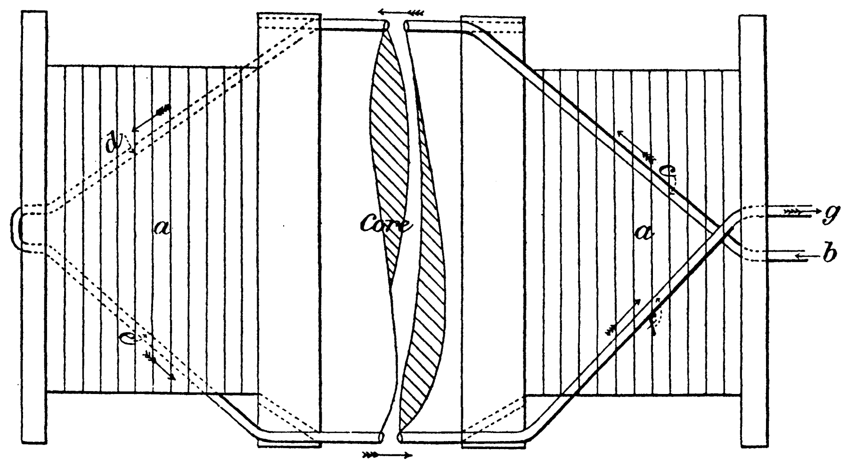


Fig. 5

standard at all loads within the capacity of the machine, excepting only a slight momentary variation when a large portion of the load is switched on or off.

The resistance from brush to brush is only 0·0032 ohm, the resistance of the field magnets is 17·7 ohms, while the normal output of the dynamo is 200 amperes at 80 volts. This, excluding other losses, gives an efficiency of 97 per cent. The other losses are due to eddy currents throughout the armature, magnetic retardation, and bearing friction. They have been carefully measured.

By separately exciting the field magnets from another dynamo, and observing the increased steam pressure required to maintain the speed constant, the corresponding power was afterwards calculated in watts.

The commercial efficiency of this dynamo, after allowing for all losses, is a little over 90 per cent. In the larger sizes it rises to 94 per cent.

Assuming the compound steam turbine to give a return of 70 per cent. of the total mechanical energy of the steam, and the dynamo to convert 90 per cent. of this into electrical output, this gives a resulting efficiency of 63 per cent.

As steam of 90 lb. pressure above the atmosphere will with a perfect non-condensing engine give a horse-power for every 20·5 lb. of steam consumed per hour, it follows that an electrical generator of 63 per cent. efficiency will consume 32·5 lb. of steam for every electrical horse-power per hour.

Again, with steam at 150 lb. pressure above the atmosphere a generator of the same efficiency would consume only 22·2 lb. of steam per electrical horse-power per hour.

The results we have so far actually obtained are a consumption of 52 lb. per hour of steam for each electrical horse-power with a steam pressure of 90 lb. above the atmosphere. We, however, expect shortly to obtain results more nearly coinciding with those very high economies that theory has led us to believe possible with this system. In the larger sizes, so far as we have yet gone, we have invariably found increased economy, as in them the clearances are proportionately less and it is easier to arrange the distribution of steam.

Exceptionally low steam consumption is not the only essential attribute of an electric generator, there are other considerations, in most cases of more importance; these are steadiness of the current produced, freedom from accident, and simplicity, small first cost and cost of upkeep, little attention required, smallness of size and weight for a given output, and an almost insignificant consumption of oil.

To illustrate this we will take the installation at the Phoenix Mills, Newcastle-on-Tyne, which has been running on the average 11 hours daily for the last two years.

Out of the original 159 Edison Swan 16-candle-power lamps 65 are still in good condition, having run 6500 hours at about standard brightness. Now, if the lamps had only lasted 1000 hours on the average, the cost of lamps renewed would have amounted to about double the year's cost of fuel as at present consumed.

At the Newcastle-on-Tyne Industrial Exhibition thirteen of these turbo-electric generators lighted the whole of the courts, giving a total of about 280 electrical horse-power.

During the whole run of the Exhibition the only noticeable accident which occurred to the installation was due to the blowing out of the packing in a branch steam pipe connecting another engine to the main steam pipe supplying the generators, but as there was no stop valve in this branch pipe, the engineer in charge deemed it prudent to shut off steam at the boilers, thus stopping all the generators lighting the four courts for about three-quarters of an hour; this, however, was an accident quite external to the generator and, as it happened, external to the main steam pipe supplying them.

We believe that there were only three occasions during the run of the Exhibition when a small group of lamps was extinguished for the few seconds necessary to enable a spare generator to be started and switched on to them.

The seventeen generators were in two groups; had they been placed in one group the results showed that on all occasions one spare generator would have been sufficient to keep every lamp alight.

In regard to simplicity and cost of upkeep, we may say that in a 30 horse-power generator there is no part that three men cannot lift, and that every part is immediately accessible.

After two years' working, of 10 hours daily, we have found the wear very small indeed, in some cases almost inappreciable, the blades, or vanes, show no signs whatever of any cutting action of the steam.

The commutators in the larger generators have generally withstood this amount of wear, while in some cases where they have been carefully attended they have suffered very little wear indeed.

We have at the present time some important experiments being carried out in regard to the generators. It would, however, now be premature to foreshadow the probable results of these trials. We may, however, say that they lead us to conclude that, most especially in the larger sizes, very much increased economy will be obtained, amounting to a reduction of from 20 to 25 per cent. of the steam consumption quoted in the paper.

We may also add that we have now supplied generators giving a total output of 1280 electrical horse-power; about two-thirds of this amount has been for ships, and one-third for land installation. This amount does not include the Newcastle Exhibition.

We have supplied generators to the English, Austrian, Italian, Spanish, Chilian, Chinese, and United States Governments. Figs. 1 and 2 are views of a typical machine showing its construction. Fig. 3 is the old flexible bearing with washers. Fig. 4 is the governor on the top of the magnets. Fig. 5 is the drum winding of the armature.

In the course of his replies to the discussion Sir Charles said: "In regard to the arrangement of turbines for high pressures, such as 150 lb. per square inch, he would say that in the larger sized generators they had adopted an arrangement called the triple compound type. In this type the turbines or wheels increased in diameter by steps towards the exhaust ends. By this means the proper distribution of steam at very high pressures could be easily dealt with in a satisfactory manner".

Cambridge University Press
978-1-107-50202-4 - Scientific Papers and Addresses of the Hon. Sir Charles A. Parsons
Edited by The Hon. G. L. Parsons
Excerpt
More information

THE APPLICATION OF THE COMPOUND STEAM TURBINE TO THE PURPOSE OF MARINE PROPULSION

Institution of Naval Architects, April 8th, 1897

It has been suggested by Sir W. H. White that a paper giving some account of the application of the compound steam turbine to the purpose of marine propulsion might be of interest to the members of this Institution.

The date of this paper is, perhaps, somewhat premature, as the *Turbinia*, the first boat fitted with turbine engines, has not as yet completed her experimental trials, but as the results so far ascertained are in some respects remarkable, this, perhaps, may afford some excuse for their publication.

The manufacture of the compound steam turbine was first commenced in the year 1885, with the construction of small engines for the driving of dynamos; successive improvements were made, and larger engines constructed, but up to the year 1892 the consumption of steam was not such as to justify the application of this class of engine to the purpose of marine propulsion, though, on account of its light weight, small size, and high speed of revolution, it presented great advantages over ordinary engines for certain classes of work.

In the year 1892, however, a highly developed compound turbine, adapted for condensing, was constructed for the Cambridge Electric Supply Company, and when tested by Professor Ewing, F.R.S., showed a consumption of steam equivalent to 15·1 lb. per indicated horse-power per hour, the boiler pressure being 100 lb., and the steam superheated to 127° F. above the point of saturation.

More recently compound turbine engines have been constructed up to 900 horse-power, both condensing and non-condensing, and consumptions of steam as low as 14 lb. per indicated horse-power with saturated steam, and 100 lb. boiler pressure, have been ascertained in engines of 200 horse-power, and still lower consumptions in engines of larger size. Many of the original engines are still doing good work; some, especially the larger sizes of 500 horse-power and upwards, are frequently kept at work for several weeks without stopping. The returns of the Newcastle and District Electric Lighting Company show a yearly cost of upkeep of $2\frac{1}{2}$ per cent. per annum, and the total horse-power of turbines now at work in England exceeds 30,000 horse-power.

In January, 1894, a syndicate was formed to test thoroughly the application of the compound steam turbine to marine propulsion, and a boat was designed for this purpose. In view of the large amount of alteration that would probably be required before a satisfactory issue was reached, and the large amount of time and expense necessarily involved, it was decided to keep the dimensions as small as possible, but not so small as to preclude the possibility of reaching an unprecedented rate of speed, should all the parts work as satisfactorily as was anticipated.

The fulfilment of these anticipations was, however, much delayed, and almost frustrated, by a difficulty which, though foreseen, proved to be of a much more serious character than was anticipated. This difficulty was that termed by Mr R. E. Froude "the cavitation of the water", or, in other words, the hollowing out of vacuous spaces by the blade of the screw, and this pitfall for the designers of screws for very fast vessels, though indicated by theory to exist, came upon us in the case of our very fast-running screw, taxed beyond the usual extent, in its most aggravated form. When the boat and machinery were designed, the trials of the *Daring*, which first drew attention to this difficulty, had not taken place.

The *Turbinia*—as the boat is named—is 100 feet in length, 9 feet beam, and 44½ tons displacement. The original turbine engine fitted in her was designed to develop upwards of 1500 actual horse-power at a speed of 2500 revolutions per minute. The boiler is of the water-tube type for 225 lb. per square inch working pressure, with large steam space, and large return water legs, and with a total heating surface of 1100 square feet, and a grate surface of 42 square feet; two firing doors are provided, one at each end. The stokeholds are closed, and the draught furnished by a fan coupled directly to the engine shaft. The condenser is of large size, having 4200 square feet of cooling surface; the circulating water is fed by scoops, which are hinged and reversible, so that a complete reversal of the flow of water can be obtained should the tubes become choked. The auxiliary machinery consists of main air pump and spare air pump, auxiliary circulating pump, main and spare feed pumps, main and spare oil pumps, also the usual bilge ejectors; the fresh-water tank and hotwell contain about 250 gallons. (See Plate III.)

The hull is built of steel plate, of thickness varying from $\frac{3}{16}$ inch in the bottom to $\frac{1}{16}$ inch in the sides near the stern, and is divided into five spaces by water-tight bulkheads.

The approximate weights are:

Main engines ... ...3 tons 13 cwt.	
	Tons
Total weight of machinery and boiler, screws and shafting, tanks, etc.	22
Weight of hull complete	15
Coal and water...	7½
Total displacement	44½