THE DEVELOPMENT OF THE MODERN WATER TURBINE.

By J. K. HUNTER, B.Sc.; A.M.I.C.E., (Messrs. Fentons, Ltd.)

LIST OF ILLUSTRATIONS.

<table>
<thead>
<tr>
<th>Figures</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70,000 H.P. I. P. Morris Turbine for the Niagara Falls Power Co.</td>
</tr>
<tr>
<td>2, 3</td>
<td>5,200 H.P. Turbines for the Winnipeg Power Station.</td>
</tr>
<tr>
<td>4</td>
<td>Vammafoss Power Station—Machine Room.</td>
</tr>
<tr>
<td>5</td>
<td>Humberam Turbine—Sectional Drawing</td>
</tr>
<tr>
<td>6, 7</td>
<td>Humberam Turbine—In Erection Shop</td>
</tr>
<tr>
<td>8</td>
<td>Humberam Turbine—Model Test Curve</td>
</tr>
<tr>
<td>9</td>
<td>Solbergfoss Turbine—Sectional Drawing.</td>
</tr>
<tr>
<td>10, 11</td>
<td>Arapuni Turbine—Sectional Drawing</td>
</tr>
<tr>
<td>12</td>
<td>Arapuni Turbine—The Runner in the Shops.</td>
</tr>
<tr>
<td>13</td>
<td>The Runner of the Honefoss Turbine.</td>
</tr>
<tr>
<td>14</td>
<td>Cedars Rapids Turbine—Sectional Drawing.</td>
</tr>
<tr>
<td>15</td>
<td>Diagram showing Runner Profiles.</td>
</tr>
<tr>
<td>16</td>
<td>Diagram showing efficiency curves for different specific speeds.</td>
</tr>
<tr>
<td>17</td>
<td>Lilla Edet Turbine—Kaplan Runner in the Erection Shop.</td>
</tr>
<tr>
<td>18</td>
<td>Lilla Edet Turbine—Diagram of Comparative Efficiency Curves.</td>
</tr>
<tr>
<td>19</td>
<td>Characteristic Curves for the Arapuni Runner.</td>
</tr>
<tr>
<td>20</td>
<td>7,500 B.H.P. Dolgarrog Turbine—Sectional Drawing.</td>
</tr>
<tr>
<td>21</td>
<td>7,500 B. H.P. Dolgarrog Turbine—In Erection Shop.</td>
</tr>
<tr>
<td>22</td>
<td>30,000 H.P. Pelton Turbine—Sectional Drawing.</td>
</tr>
<tr>
<td>23</td>
<td>5,000 H.P. Turbines at Hakavik, Norway.</td>
</tr>
<tr>
<td>24</td>
<td>Pelton Runner for Hakavik, Norway.</td>
</tr>
<tr>
<td>25</td>
<td>Pelton Runner for Dolgarrog Turbines.</td>
</tr>
</tbody>
</table>
THE DEVELOPMENT OF THE MODERN WATER TURBINE.

By J. K. HUNTER, B.Sc.; A.M.I.C.E.
(Messrs. Fentons, Ltd.)

Introductory.—Water-power was probably the first of Nature's stores of energy to be tapped and harnessed by mankind. Power was developed in ancient times by the impact of flowing streams upon flat wooden paddles fixed around the periphery of a wheel. Such a device is described by the architect and engineer Vitruvius in 14 B.C., and even at the present day similar crude machines may be seen working in remote corners of the world. These rough wheels, which returned but a small fraction of the energy imparted to them, were the forerunner of the modern highly efficient hydro-electric plants to be described hereafter.

Up to the end of the eighteenth century water-power was extensively used in Great Britain and the principal European countries for industrial purposes especially for milling and the manufacture of textiles and in consequence, there was a tendency for the early industrial communities to grow up around river sites. The advent of the steam engine, however, and the construction of railways led to the gradual disuse of many water-power installations, and it was not until the latter-end of the last century that interest in water-power began to revive.

The very remarkable increase in the use of water-power since 1880 is largely attributable to the introduction and perfection of electrical generating and transmitting machinery which has made it possible to develop enormous blocks of power in remote isolated spots and economically transmit it, in some cases several hundreds of miles, to industrial centres, where, by means of the electric motor, it may be readily utilized for driving factories and workshops.
Another very important factor which has been largely responsible for the ever-increasing activity in the hydro-electric field, especially since the War, is the growing realization of the urgent necessity for rigorous economy in the consumption of coal and oil.

Herein lies one of the most fundamental differences between fuel and water-power, for whereas in the former case energy is withdrawn and dissipated from a definite and strictly limited store, which has taken million of years to build up, water-power is derived from a non-wasting source, which although of course limited as to quantity, is yet perpetually replenished through the agency of the sun.

The water-power resources of a country form one of its most valuable national assets, and the realization of this has, in recent years, led the Governments of the majority of European countries to undertake a careful survey of their potentialities and to take the development of water-power sites under state control.

The modern water turbine is the most efficient prime mover known, over-all efficiencies in excess of 93% having been obtained in several recent large plants, while efficiencies of 90% are now looked upon as of everyday occurrence. Such performances, of course compare very favourably with the efficiencies possible from the most modern steam turbines and Diesel engines.

The highest efficiencies yet obtained from a steam turbine do not exceed 26% from coal to coupling, while 32% is about the best return which can be expected from a Diesel plant.

Historical.—The earliest reaction turbine as we know it to-day was evolved by M. Fourneyron about 1823. In this machine the guide vanes were inside the runner, the water being fed into the centre of the wheel whence it flowed radially outwards. This type was superseded by the Jonval turbine, in which the guide vanes were above the runner, the water flowing through the wheel in an axial direction. Both these early types have been obsolete for the past twenty years and have given place to the Francis type. As originally designed this turbine was of the radial inward flow type, the guide vanes surrounding the outer
periphery of the wheel. Later it developed into the modern mixed-flow reaction turbine, in which the water initially enters the runner in a radial direction and is deflected in its passage through the buckets so that it leaves the wheel in a direction parallel with the axis of the turbine.

Of the early impulse wheels the Giraud type was one of the first to be developed in Europe. The wheel itself was very similar to that of the Fourneyron turbine, but in this case the water was usually admitted to the wheel over only a portion of its inside periphery, the whole energy of the water being converted into kinetic energy before entering the buckets.

Side by side with the Giraud turbine in Europe the "Hurdy Gurdy," a tangential form of impact wheel, was evolved by the old American pioneers. In this wheel the water was directed in a jet upon flat buckets fastened around the periphery of a wheel, and it was from this crude type that what we know as the Pelton wheel has since been developed.

The Modern Water Turbine.

Water Turbines may be divided into two distinct classes: the Impulse class and the Reaction class, the name in each case indicating the principle on which the energy is extracted from the water. Practically speaking these two classes are represented by only two present-day types: the first named by the Pelton Wheel and the second by the Francis Turbine.

Other types have, of course, been evolved in recent years, but they have not come into general use and their discussion is outside the scope of this paper.

In any Impulse Turbine the whole head of the supply water is converted into Kinetic Energy before the wheel is actually reached. The water leaves the nozzle in the form of a high-velocity jet which passes freely through the air filling the turbine casing and impinges upon the buckets of the wheel, the pressure of the water remaining constant (usually atmospheric) throughout its passage through the turbine.

The Pressure or Reaction Turbine, on the other hand, consists of a wheel or "runner" fitted with curved vanes (usually referred to as "buckets")
into which the water is directed over the entire periphery by a series of guide vanes arranged in a ring surrounding the wheel. The water leaving the guide vanes is under pressure and supplies energy to the wheel partly in the pressure and partly in the kinetic form.

General Comparison Between Impulse and Reaction Turbines.

The peripheral velocity of a Pelton wheel is usually rather less than half the spouting velocity of the jet (\( \cdot 46 \sqrt{2gH} \) is an average value), while that of a Reaction Turbine varies, according to design, from \( \cdot 65 \sqrt{2gH} \) to \( 1.05 \sqrt{2gH} \). Hence the Reaction type in general enables higher speeds to be obtained, and this property is of special importance under low heads. The Pelton Wheel on the other hand is particularly well adapted for operation under high heads. The latter type, however, cannot readily be designed to utilize more than two jets on a single wheel, and as the maximum practical jet diameter is about 8 inches, the volume of water which can be handled, and hence the output, is small under low heads. The Reaction type, on the other hand, with its full peripheral admission is well suited for dealing with large volumes of water, but is not adapted for small powers under high heads, since the water passages become small and hence are easily choked and also the fluid friction losses become high.

The Reaction Turbine lends itself readily to the use of a draft tube, and thus the head between the wheel and the tail race is fully utilized—a very important matter in the case of very low head plants. A well designed Reaction Turbine has a rather higher full load efficiency than the Pelton Wheel, but against this, however, its efficiency on part loads falls off more rapidly than in the case of the latter type. Owing to its greater simplicity and accessibility, the Pelton Wheel is more suited to cases where the water carries much sand in suspension, and further there is no loss of power from increased leakage as in the case of the Reaction Turbine, where a high efficiency is dependent upon the maintenance of fine clearances around the runner.

Specific Speed.—For the purpose of accurately comparing various types and designs of water turbines, a characteristic termed the "Specific
Speed has of late years been universally adopted by water-power engineers, and in order that the spheres of usefulness and the limitations of the various types to be described hereafter may be made clear, it will be necessary to explain at some length the definition and derivation of the term.

The specific speed of a turbine runner is defined as that speed at which the runner would rotate if, without in any way changing the design, it were so reduced in size that it developed unit power when operating under unit head.

To determine the specific speed of a given runner, let:

- \( P \) = Output
- \( N \) = Speed
- \( Q \) = Discharge
- \( H \) = Head

Then since the velocity of the water, and hence the peripheral speed of a runner for maximum efficiency, is proportional to \( \sqrt{H} \), we have for a given turbine:

- \( N \propto \sqrt{H} \)
- \( Q \propto \sqrt{H} \)
- \( P \propto H \times Q \propto H \times \sqrt{H} \propto H^{3/2} \)

Without altering the dimensions, reduce the head from \( H \) to \( h \) then:

\[
\frac{n}{N} = \sqrt{\frac{h}{H}} \times \frac{P}{P} = \left( \frac{h}{H} \right)^{3/2}
\]

Now reduce the diameter of the runner from \( D \) to \( d \)

\[
\frac{p}{P} = \left( \frac{h}{H} \right)^{3/2} \times \left( \frac{d}{D} \right)^{2}
\]

i.e.,

\[
\frac{D}{d} = \left( \frac{P}{p} \right)^{1/3} \times \left( \frac{h}{H} \right)^{2/3}
\]

Also

\[
\frac{n}{N} = \sqrt{\frac{h}{H}} \times \frac{D}{d}
\]

\[
= \sqrt{\frac{h}{H}} \times \frac{P}{p} \times h \left( \frac{h}{H} \right)^{2/3}
\]

\[
= \sqrt{\frac{P}{p}} \times \left( \frac{h}{H} \right)^{5/6}
\]

If \( h \) and \( p \) be made unity

We have the specific speed \( N_s = N \cdot \frac{\sqrt{P}}{H^{5/6}} \)
The specific speed may of course be stated in either English or Metric units, the value in the latter case being 4.45 times the corresponding value when stated in English units.

The range of specific speed for modern reaction runners varies from about 13 to about 150 (English units) or even more in extreme cases; while that for the Pelton Wheel usually ranges from about 2.3 to about 7.3 for a wheel using a single jet, or up to about 10.3 if two jets be used upon a single wheel.

It will be noticed that if we confine ourselves to the two principal types of Turbines under discussion, their respective speed ranges do not overlap, but that there is a certain range to which neither type can be readily adapted, and it is for this reason that the efforts of many designers have of late been directed towards the evolution of a new type of turbine whose specific speed range shall fill up the gap which now exists between the widely used Pelton and Francis types.

THE FRANCIS TYPE REACTION TURBINE.

The Guide Apparatus.—Speed regulation is effected by controlling the admission of water to the turbine runner, usually by one of the following methods:—

(1) Cylinder Gate
(2) Register Gate
(3) Wicket Gate

In the first-named method the runner and fixed guide vanes are surrounded by a cylinder controlled by rods passing through stuffing boxes in the crown plate of the turbine by means of which it can be moved in an axial direction, and the annular opening around the runner thus altered at will.

The second method consists in surrounding the runner by what is virtually a fixed cylinder carrying a series of openings around its circumference, this again is surrounded by a movable cylinder
carrying slots corresponding to those provided in the fixed cylinder, and by giving the former a slight rotary motion; the slots admitting water to the wheel may be opened or closed as desired.

Owing to the eddies caused by these two methods of regulation at part gate opening, the efficiency of the turbine is seriously impaired on small loads, and for this reason they have been superseded by the more modern wicket gate. This consists of a series of pivoted guide vanes mounted upon spindles surrounding the runner and connected together by links and arms in such a way that they can all be given a slight rotational movement and thus the opening between the guide vanes can be varied.

**Turbine Settings.**—The water may be delivered to the guide apparatus in a variety of ways, the simplest of all consisting of merely setting the turbine runner with its surrounding guide apparatus in an open pit or flume. Such a method is obviously limited to low head installations and it has the advantage of cheapness and general simplicity, although it usually necessitates the moving parts controlling the guide apparatus and one or more of the turbine bearings being submerged. A typical installation where the open flume setting has been adopted for a large horizontal shaft double runner unit is shown in figs. 2 and 3, which give a section and plan through one of the 5,200 H. P. turbines at the Winnipeg Hydro-Electric Power Station on the Winnipeg river. This station, although built in 1911, is still typical of modern practice where this type of lay-out is adopted. The turbines which were supplied by Messrs. Jens Orten Boving & Co. work under an average head of 45 ft. and run at 164 r.p.m., being direct coupled to 3,000 K.W. alternators.

In cases where the head is too high to readily admit of the adoption of the open flume setting the turbine runner or runners together with the guide apparatus is encased in a cylindrical steel drum which is connected via a pipe line with the source of water supply. A large modern installation where such an arrangement is in use is shown in figs. 4 and 5 which show the machine room of the Vammafoss Power Station on the Glommen river in Norway. These turbines, which are physically
The Development of the Modern Water Turbine

The largest in Europe, are of the horizontal shaft double runner type, and operate under a head of 28 m (92 ft.) the first units, installed develop 12,000 B.H.P., while the last one to be put in develops 16,000 B.H.P. Four of the seven units shown were supplied by Messrs. Jensen and Dhal, while the remaining three were constructed by Messrs. Kraemer Brug, both of Oslo.

Under still higher heads, where considerable pressures and water velocities have to be dealt with, it is usual to enclose the runner in a spiral casing by means of which the water may be fed into the guide apparatus at all points of its periphery at a uniform velocity and without the setting up of considerable eddies due to sudden changes of section such as occur in the case of cylindrical cased turbines. The spiral casing may be made of cast iron, cast steel, rivetted plate steel or, in large low head units of the vertical type, reinforced concrete.

A recent installation where the horizontal shaft single runner spiral turbine was adopted is shown in figs. 6, 7 and 8, illustrating one of the seven 14,000 B.H.P. units constructed by Messrs. Sir W. G. Armstrong Whitworth & Co., Ltd., for the Humberarm Development in Newfoundland. In these turbines the spiral casing, which has an inlet diameter of 5 feet 6 inches, is of cast steel and is made in three sections. The tests on the model turbine built in connection with this plant gave remarkably good results, a full load efficiency of 90% being realized as indicated in the accompanying reproduction of the test curve (fig. 9).

For very large units operating under low and medium heads the vertical shaft single runner turbine has of late years come into prominence. This arrangement offers many advantages over the previous stage of water turbine development which featured the horizontal shaft and multi-runner units. Its simplicity of design, superior hydraulic conditions and economy of space have resulted in the last few years in its general adoption for very large turbines throughout the world.

In view of its importance several examples are given of this type of unit. Fig. 10 shows a section through one of seven units recently put into service at the new Solbergfoss Power Station on
the Glommen River, Norway, and forms an interesting example of the way American practice has influenced European designers during the past few years. These turbines which each develop 11,500 B.H.P. operate under a head of 21 m (69 ft.). The spiral chamber surrounding the turbine proper is in this case built of concrete and forms an integral part of the power house structure. By adopting such methods of construction smooth sweeps can readily be obtained for the water passages and great rigidity and freedom from vibration is assured.

Fig. 11 illustrates a section through one of the three 25,000 B.H.P. turbines now being built by Messrs. Sir W. G. Armstrong Whitworth & Co. for the Arapuni Hydro-Electric Scheme in New Zealand. The turbines which are designed to work under a head of 172 ft. run at 214 r.p.m., the spiral chamber in this case being built up in sections from steel plates, which are rivetted to the split cast steel speed ring which houses the guide apparatus.

As a representative example of the most recent American practice an illustration is given (see Fig. 1) showing one of the new great turbines recently installed by the I. P. Morris Dept. of Messrs. Wm. Cramp & Sons for the Niagara Falls Power Co. (Station No. 3c). These turbines, of which there are three (two built by I. P. Morris, and one by the Allis Chalmers Mfg. Co.), each develop 70,000 B.H.P. and are the largest prime movers in the world. In the unit illustrated the turbine casing is of the cast steel sectional type with stay vanes cast integrally, the generator being supported directly by the concrete substructure of the power house.

Turbine Runners.—It is quite outside the scope of this paper to attempt a discussion of the hydraulics of the reaction turbine or to enter into the theory underlying runner design, and it is therefore merely proposed to briefly refer to some of the chief types of reaction wheels at the same time outlining their various characteristics.

Fig. 12 illustrates one of the runners for the 25,000 B.H.P. Turbines for the Arapuni Power Station in New Zealand, previously referred to.
This runner which is 2,400 m.m. in diameter is of the medium specific speed type: the buckets are forged separately from steel plates in a hydraulic press and are afterwards cast into the steel hub and band.

Fig. 13 shows a typical runner of a moderately high speed type, and illustrates one of the runners built by A. S. Kvaener Brug for the Honefos plant in Southern Norway. The method of manufacture in this case was the same as that described for the Arapuni Runners.

Where runners reach excessive dimensions, as is the case with many large low-head installations, it is usual, from manufacturing considerations, to cast them in two, or sometimes, four segments which are afterwards bolted or dovetailed together. Such a procedure was adopted in the case of the Cedar Rapids turbine illustrated in Fig. 14.

A common method of construction, especially in America, consists in casting the buckets integrally with the hub and band at one pouring of the mould. This method produces a very rigid wheel, but it calls for a high degree of skill on the part of the moulder where large sizes are being dealt with, and it has the disadvantage that the resulting surfaces are rougher and more irregular than those obtained by using separate pressed steel buckets.

In Fig. 15 is shown a diagram illustrating the way in which the profile of the buckets and the general form of a reaction runner change with increasing specific speed. The upper figure shows a low specific speed runner \((N_s = 65 \text{ metric})\) and it will be observed that the water passages are long and narrow, and that the diameter of the discharge side is small compared with the inlet diameter. The second figure shows a typical section through a medium specific speed runner \((N_s = 175 \text{ metric})\), while the bottom figure illustrates a high speed type \((N_s = 400 \text{ metric})\) from which it will be seen that the runner has extended in an axial direction giving large water passages, and that the greatest diameter of the discharge edges of the buckets now exceeds the inlet diameter.

In Fig. 16 is a diagram which clearly illustrates the effect upon the shape of the efficiency curve of increasing the specific speed of a
turbine, and it will be noticed that in general the part load efficiency of a runner falls off as the specific speed is increased. This factor is of course an important consideration where a unit is called upon to operate at small loads for long periods, since it means that the water consumption for a given power output is unduly increased. In practice, however, the poor efficiency obtainable from high speed runners at part loads is not such an important factor as would appear at first sight, since nearly all modern power stations of any magnitude are of the multiple unit type, and it is thus possible to arrange for all or nearly all of the machines to be working under practically full load.

As the specific speed is increased, the tendency is for the runners to become more and more of the axial type, and if we take some of the exceedingly high speed runners of the present day, e.g., the Moody type in America or the Kaplan and Lawaczeck type in Europe, we will see that the flow is almost entirely axial.

A photograph is given (fig. 17) of the Kaplan runner for one of the Lilla Edet turbines in Sweden, and the striking resemblance to an ordinary ship's propeller will be noted. In this type, the blades, of which there are only four, can be pivoted about the hub through the medium of suitable mechanism contained therein, and by this means the angle of inclination, and hence the hydraulic design, of the blades may be altered at will to suit the varying load conditions. The very remarkable advantage to be gained from the ability to thus alter the design whilst the turbine is actually working is clearly brought out by a comparison of the two curves shown on diagram 18, which gives the efficiency curve obtained from the 10,000 B.H.P. Kaplan Turbine at Lilla Edet compared with that obtained from a similar turbine in the same power station where the Lawaczeck type of fixed blade high speed runner has been adopted.

The Draught Tube.—After passing through the runner, the water, in the case of a reaction turbine, is discharged into the draught tube, the lower end of which is sealed beneath the tail race water. By this means the turbine can be placed at some
convenient height above the tail water level without any loss of effective head, the maximum practical elevation depending upon the diameter of the draught tube as also of course, upon the barometric pressure at the site.

In addition to this, the draught tube serves the very important function of recovering part of the kinetic energy of discharge from the runner. The mean velocity of discharge from a reaction runner varies, according to the specific speed, from about \( \sqrt{2gh} \) in a slow speed machine to about \( \sqrt{5gh} \), or more, in the case of a high speed turbine operating under a low-head. This latter value means that 25% of the total energy of the water is discharged from the runner into the draught tube, and hence the importance of efficiently recovering this energy is obvious.

During the last few years the development of the draught tube has been almost as marked as that of the high speed reaction runner. The water leaving the buckets of a high speed runner has, at part loads, a very considerable velocity of whirl in addition to its axial velocity component, and it is for the purpose of recovering the whirl component that the spreading type of draught tube has been adopted for many of the large plants recently constructed in America.

A typical example of the Moody draught tube can be seen in Fig. 1 illustrating one of the new 70,000 H.P. turbines for the Niagara Falls Power Co. to which reference has already been made, and it will be seen that in this instance the internal cone which forms a feature of the Moody draught tube has been taken right up to the boss of the runner, sections through the draught tube normal to the flow thus taking the form of annular spaces of ever increasing area.

The Pelton Water Wheel.—Except in the case of very large plants, the vertical shaft setting is rarely adopted for Pelton wheels. The arrangement which has come into favour in recent years consists in overhanging the runner upon an extension of the generator shaft, and thus eliminating the turbine bearings entirely. An example of such a lay-out is shown in figs. 20 and 21 which illustrate one of the two 7,500 B.H.P. Turbines.
supplied by Messrs. Sir W. G. Armstrong Whitworth & Co., Ltd., to the Dolgarrog Power Station of the Aluminium Corporation, N. Wales. Fig. 22 illustrates a similar arrangement where the double overhung runner has been proposed for some 30,000 B.H.P. Turbines for the Tata Plant in India.

Fig. 23 shows the Machine Room of the Hakavik Power Station in Southern Norway, where are installed three 5,000 H.P. Pelton Turbines operating at a head of 390 metres (1,280 ft.). The runner of one of these units is shown in Fig. 24 assembled in the makers' (Messrs. Jensen & Dhal) shops. The heavy ribs at the back of the buckets, which are of cast steel, and the method of fixing them to the disc are clearly shown.

Fig. 25 shows the Runner of one of the 7,500 H.P. Dolgarrog Turbines assembled for balancing. The much smaller ratio in this case between the diameter of the bucket pitch circle and the width of the buckets will be noted.

Factors Affecting the Efficiency of Pelton Wheels.—The energy of a jet issuing from a well designed nozzle is about 98.5% of the total energy of the water. Jet distortion is one of the chief causes of loss of efficiency in impulse turbines. The proper formation of the jet depends largely upon the nozzle itself, but it is also greatly influenced by the design of the supply piping, such factors as the velocity of the water in the supply pipe, the radius of curvature in the bends, their relation to one another, the smoothness or otherwise of the walls of the pipe—all having their effect.

Sharp bends at the back of the nozzle tend to set up a rotational motion of the water stream, the resulting centrifugal forces causing the jet to spread; this is perhaps the most common cause of poor jet formation, and it is common practice to fit guide vanes in the inlet pipe immediately behind the nozzle in order to eliminate any rotation set up by bends in the supply piping.

The head under which the plant operates also affects the jet formation; it being more difficult to obtain a good jet under a high head than under a low one.
Another very common cause of poor efficiency, especially in the older designs is mutual interference between the jets in cases where two or more jets work upon a single runner. The angle between the jets should not be less than 80° and the turbine casing should be so designed that the discharge water from the upper nozzle does not interfere with the lower jet. Best results can always be obtained when a single jet is used on each runner, increased output being obtained by employing two runners, either side by side, or, one at each end of the generator shaft.

There are two very important relations governing the efficiency of a Pelton wheel:

(a) The ratio of the pitch diameter of the buckets to the diameter of the jet.

(b) The ratio of the bucket width to the jet diameter.

Generally speaking the smaller the ratio of the pitch diameter of the buckets to the diameter of the jet, the more difficult it is to design a wheel to give a good efficiency, and further progress in Pelton wheel design will undoubtedly be in the direction of obtaining good performances where this ratio is small.

Upon the relation between the bucket width and the jet diameter depends the percentage of full load at which the turbine gives its best efficiency and by altering this ratio the character of the efficiency curve can be changed as desired.

The Regulation of Impulse Turbines.—Generally speaking the Pelton Wheel is installed where high heads have to be dealt with necessitating long pipe lines, and since, for economic reasons, high pipe line velocities are imperative, any sudden change in the flow would induce dangerous pressure rises. The combined flywheel effect of turbine and generator is usually fairly small, and it is therefore necessary for satisfactory speed regulation, that the power input to the wheel shall be capable of being rapidly altered to suit changes of load.
In the case of Pelton turbines, the speed regulation is accomplished in a variety of ways, the chief of which are:

(a) Deflecting the jet from the wheel.

(b) Closing the jet by a spear regulator and by-passing the water.

(c) Spear regulator combined with deflecting the jet.

Taking the first mentioned method, this is usually effected by:

1. Mounting the inlet pipe carrying the nozzle upon trunions in such a way that the whole jet may be swung clear of the wheel.

2. Using a fixed nozzle and deflecting the jet from the buckets by means of a movable deflector or "knife" which can be brought into the jet either from above (the deflector) or from below (the knife) and thus throwing all or part of the jet away from the wheel.

Both these methods do not of course economize water, the nozzle always running full bore and hence can only be used in very small plants or in cases where it is obligatory upon the power company to at all times pass a constant flow of water.

The second method of regulation (b) is effected by quickly closing down the jet by means of a spear regulator and at the same time opening up a by-pass valve (which usually takes the form of a spear controlled nozzle similar to the nozzle proper). When used in conjunction with an automatic governor, this by-pass nozzle is so arranged that, after opening, the needle valve is again brought back to its seat, thus preventing unnecessary waste of water. This method of regulation is much used by The Pelton Water Wheel Company of America, and whilst giving a ready means of control, has the disadvantage, that under the high heads usually obtaining in Pelton plants, the seat of the by-pass valve is subject to rapid wear and considerable leakage occurs after the plant has been in use for some years.
The Development of the Modern Water Turbines

The last named governing device is perhaps the most universally adopted at the present time, and consists in combining a slow moving spear controlled nozzle with a quick acting deflector. Fig. 20 shows a typical plant where such a method is in use—the hood-like deflector being clearly seen above the projecting spear tip.

In the plant illustrated in Fig. 22 an upward moving knife is used instead of the deflector—the effect being the same.

Perhaps the most recent development in the regulation of impulse wheels is that known as the Seewer System where the tendency of a rotating jet to spread under the action of centrifugal force is made use of to destroy or partially destroy the jet when it is desired to reduce the power input to the wheel.

The jet issuing from the nozzle is given a rotational motion by means of a set of movable vanes, incorporated in a special spear head. Under steady operating conditions these vanes are withdrawn into their sheaths but under the action of the governor a reduction in load causes them to be projected into the water stream, imparting to it a rotary motion.

Model Turbines.—Mention should be made of the important place held by experiment in the development of the art with which this paper deals. The progress of all scientific knowledge depends ultimately upon our ability to accurately observe facts and upon such observations we build our generalized theoretical structure which in its turn is revised until it stands the test of practical experience.

Of all branches of Science the theory of Hydraulics is perhaps more than any other dependent upon practical research, and there can be little doubt that the great advancement in the performance of water turbines made during the past fifteen years is largely attributable to the way in which theory has been developed co-laterally with experimentation. In nearly all the more important water power installations, it is the usual practice for the water turbine contractors to build an exact small scale model of the proposed turbine and thoroughly test it out in a
laboratory before putting the manufacture of the full size unit in hand. The laws of hydraulic similarly hold good for water turbine runners and from the test results of a model wheel can be predicted with certainty the performance of the full size runner when operating under any given set of conditions.

During the tests of a model turbine the head is usually maintained as nearly as possible constant, and the output and efficiency are measured for a series of gate openings and speeds. From these results speed-power and speed-efficiency curves are plotted for a series of gate openings, and in order to show graphically what the behaviour of the runner will be under any given conditions, a series of "characteristic curves" is drawn up. An example of such a diagram is reproduced in Fig 19 which shows the characteristic curves of the test runner built in connection with the Arapuni turbines.

Briefly, the method of constructing such a diagram is as follows: The results of the tests are reduced to those corresponding to unit head (metric units are used in the example given). The speed-power curves for this head are then drawn for the various gate openings, and are shown by dotted lines on the diagram. From the speed efficiency curves (also reduced to unit head), the speeds at which the same efficiencies are obtained at different gate openings are obtained. These speeds are marked on the corresponding speed-power curves, and through these points continuous contours of equal efficiency are drawn; these contours are the characteristic curves for the particular runner in question.

Various outside influences affect the relative performances of model and full size turbines, as the dimensions of the runner increase, the effect of fluid friction is reduced and hence, other factors being equal, the efficiency of a large turbine can always be relied upon to be in excess of that obtained from the small scale model.

Efficiency—Its Economic Aspect.—The cost of the water turbine plant in the average hydro-electric installation does not usually exceed 5% of the total cost of the scheme and is frequently considerably less than this figure. It is therefore
of the first importance that the water turbine, which may be considered as the heart of any power scheme, towards which many elements converge and away from which the converted energy radiates, should be as highly efficient and reliable as human skill can make it.

Power companies and consulting engineers are in general fully alive to the fact that it is in their own interests to purchase the best possible generating plant procurable, and to this end it is not uncommon for the power company to allocate to the successful competitor for a contract a certain sum of money over and above the contract price of the turbines for the sole purpose of carrying out special experimental work.

As a striking commentary on the advances made in turbine design, especially during the last decade, mention may be made of a scientific paper read by Mr. Eric Bergstrom before the Institution of Mechanical Engineers in 1912 in which he drew attention to the then remarkably high efficiency of 85%, which had at that time been obtained in certain plants and gave it as his considered opinion that the limit of attainment had been reached.

A Comparison of European and American Turbine Practice.

During the latter half of last century, the water turbine was developed simultaneously in Europe and America though on somewhat different lines. The early American turbine builders had but a scanty knowledge of the laws of hydraulics, and mainly depended for their designs upon rule of thumb methods and the skill of their pattern makers; relying for progress upon the practical experience gained from each successive stage of development.

In Europe on the other hand, although of course the earliest water turbines were mainly the production of simple craftsmen, yet engineers and scientists, especially in Germany and Switzerland, very soon began to tackle the problem from a different standpoint, and an elaborate theoretical structure was gradually built up by European designers upon which their water turbine designs were based. Thus it is that so many of the older
American water turbines were designed and often built in Europe, for, when it came to dealing with high heads or large units, the limitations of their theoretical knowledge were frequently made evident.

Competition in prices between European manufacturers has been much more keen than between American manufacturers, and in consequence European firms in general have not had a sufficient margin of profit to permit of extensive experimental work. During the last decade, however, turbine manufacturers have woken up to the advantages of being in a position to conduct thorough tests upon any new designs they evolve, and at the present time most of the large European firms have their own testing laboratories.

Water turbine practice has been changing rapidly of recent years both in America and in Europe, and the two lines have tended to come closer together as the art has advanced. The influence of American practice may be seen in Europe by the adoption of the large vertical single runner unit in many recent low-head installations.

So far as mere magnitude and number of plants are concerned, there is no question but that American engineers are pre-eminent. Very large units involve their own special mechanical problems but hydraulic design is not greatly affected thereby, and the achievements of European designers in the field of high speed, efficiency and reliability have never been surpassed.

The Trend of Development.—Of recent years the tendency in the Hydro-Electric field has been towards larger and larger units of the single runner vertical shaft type. This type holds many advantages over the older and more common multi-runner horizontal shaft type, and its general adoption has largely been made possible by the successful solution of the thrust bearing problem since the introduction of the Kingsbury or Mitchell bearing.

With this type of unit operating under low and medium heads the question of speed is, for economic reasons, of great importance, and in consequence the energies of designers have of late years been largely directed towards the pro-
duction of turbine runners of high specific speed. As an example of the success which has attended their efforts in this direction, a comparison may be made between the turbines of the Cedars Rapids Plant (Fig. 14) of the Montreal Light, Heat & Power Co., built in 1914, and the turbines of the State owned power station at Lilla Edet in Sweden which have recently been put into service. The Cedars Rapids units develop 10,800 H.P. under a head of 30 feet and run at 55.6 r.p.m. This is equivalent to a specific speed of 83.3 English units (370 metric) and was, at the time, the highest specific speed obtainable. On account of this low speed the generator is of very large dimensions, the outside of the stator frame being over 37 feet in diameter.

The new turbines at Lilla Edet each develop 10,000 H.P. under an average head of only 21 feet and run at 62.5 r.p.m. which corresponds to a specific speed of 132 English units (600 metric). A photograph is given (Fig. 17) showing the runner of the Kaplan unit for the Lilla Edet plant assembled in the makers' shops. Had the Cedars Rapids type of runner been used in this case the speed would only have been 38.5 r.p.m., and the dimensions of the plant would in consequence have become so great as to make the cost of the installation prohibitive.

Even higher speeds than have been adopted for the Lilla Edet turbines have recently been obtained both in Europe and in America; Kaplan type turbines having the remarkably high specific speed of 220 English units (1,000 metric) having been successfully constructed. High speed turbines have very considerable economic value in that they render practicable the utilization of many power sites, involving low falls which would otherwise be impossible owing to the high capital cost of the machinery and power house buildings.

It may be safely predicted that progress in water turbine design will for some years to come be directed towards the further development of the high speed runner suitable for operating under widely varying heads, and it is not until considerable strides have been made in this direction that the utilization of the potential value in tidal estuaries will become practicable.
DISCUSSION.

9th Paper

Mr. D. J. WIMALASURENDRÁ.—Mr. President and Gentlemen, we have heard a very interesting paper from Mr. Hunter, who has put in a very lucid and concise manner a very difficult subject which has offered much matter for thought and investigation to engineers and scientists from 3000 B.C. to the present day. It is extremely difficult to master the laws of hydraulics, though this was the very first form of power mankind used. Its principles are difficult and the scientific rules underlying its use are little understood yet. We read that in 3000 B.C. the Egyptians used this power from the Nile for milling and irrigation purposes. We read of the implements of stone they succeeded at that age in the form of stone miller to use kinetic energy out of the flowing water. Until the discovery of steam, water power remained in use, even a century after the use of steam was invented. To the feasibility of transmitting to long distances electrical energy generated by water power is due the great developments that have taken place in all parts of the world to-day in the contribution of "white coal" with "black coal." One of the most interesting points I read in this paper is the experience to the development and use of draught tubes and the effect it has had in utilizing low-heads for generating power. I see from the illustrations of some parts of the works at Arapuni described by the author, that these works have been described with much ingenuity and skill. I saw a low-head plant at Altengartau, a few miles from Zurich, developing 25,000 horse power in single units, working under a 25 foot head. Another important point the author referred to is the use of the propeller type of runners. I am of opinion that these are-
MACHINE ROOM OF VAMMAFOSS POWER STATION, NORWAY.

Fig 4.
HUMBER ARM

ARRANGEMENT OF SPIRAL FRANCIS TURBINE (LONGITUDINAL SECTION)

N: 4000 HP max.
Heff: 7.7 metres
n: 375 R.P.M.

Scale: 1" = 100 mm

Dag No. M 50150
Fig. 9

Model Runner (Size 1/3)

Of

Humber Arm Turbine

Efficiency Curves

Tests Aug 29 1923

HP for Test Turbine: 1 metre Head $\rightarrow N$

HP for Humber Arm Turbine: 7.7 metres Head $\rightarrow N$
P. TURBINE, SOLBERGFØSS POWER STATION, NORWAY.
Fig. 14.

Fig. 15.
Types of Reaction Turbine Runners

showing comparative sizes of runners for same output under unit head.

Fig. 15.
 Typical Efficiency Curves for Reaction Turbine Runners

Fig. 16.
ARAPUNI TEST RUNNER:
Diam. 460 m; l = 135 m; H_e = 4.464 m
Test No. 30 - 12.9.25. (4)

n_3 = 240

Full size runner: 2400 m³/m
25,000 B.H.P. 172 ft. 214 r.p.m.
ARRANGEMENT OF FELTON TURBINE P. 2406-42
TRANSVERSE & LONGITUDINAL SECTIONS
H = 750 FT. H.P. = 650 - 1500. N. = 450 R.P.M.
Fig. 23.

MACHINE ROOM OF HAKAVIK POWER STATIC NORWAY.
is wonderful to look at but I can assure you that it was not due to any faulty design of
going to revolutionize design and construction of water-motors. The further development of this type of runner will help to solve the difficulty of utilizing economically ranging heads for generating power.

Another point the author details deals with the design of the pipe line and its effect on efficiency of turbine operation. The correct design of a pipe line, is a difficult and complicated question and the author has dealt with the rudimentary principles involved in an able manner. Governing of water turbines, which the author has dealt with in this paper is another difficult question. Different methods of governing are described by Mr. Hunter in his paper. He refers to the Seewer System, which I think is a very ingenious and effective essential in the one. This system is adopted by the English Electrical Co. of Rugby. It consists of a series of blades mounted on the spear head and come into operation under the action of the governor and diffuse the jet impinging on the impeller. Mr. Seewer whom I have the pleasure of knowing personally explains the principle of journey as that of “tricking” the huge force involved in a water jet instead of baffling or obstructing it as done with the ordinary practice of governing in use. One can imagine what the force of a water jet 4 or 5 inches in diameter and working under a 1,500 feet head can be and what pressure will be executed on an obstruction placed across it. To break or diffuse this force Mr. Seewer introduced the “spear blade system.” It is undoubtedly very very cleverly designed and passed in theory. How far it will be successful in practical operation is a point which has got to be carefully watched. This system of governing is adopted in the three 25,000 h. p. generator units built for the Tata Power Plant in Bombay and is said to be a great success.

I had the pleasure of inspecting the two 5000 K.W. Pelton Wheel generator sets built by Messrs. Armstrong, Whitworth & Co. and installed at Dolgarrog a scheme which had an unfortunate fate. I am not aware whether the plant suffered in any way. Mr. Hunter will, perhaps, be able to tell us what happened. I can, however, assure you that it was not due to any faulty design of
the generators that the scheme suffered. As far as I am aware, it was due to a certain Civil Engineering firm who have had no experience in Hydro-Electric work attempting to design and instal this very difficult work of the pipe line. I am only sorry I have not been able to go through this paper as I would have wished to do. It affords very interesting material that has very cleverly been collected and put into such small compass. I think every engineer interested in Hydro-Electrical work will be well advised to go through it carefully.

Mr. HUNTER.—Mr. Wimalasurendra makes mention of the disaster at the Dolgarrog Hydro-Electrical Works in North Wales, and I think it well to say here that this disaster did not reflect on any firm in existence to-day. It was due to the failure of a masonry dam built sixteen or seventeen years ago and the firm of contractors who undertook that work subsequently went out of business. With regard to the Seeuer System of regulation for Pelton wheels, I remember seeing one of the first plants which the English Electric Co. constructed for the Kinlochleven (Scotland) Power Station where they installed a 3,399 h. p. unit from which were obtained very satisfactory results. Mr. Seeuer's system of automatic regulation has recently been used in connection with a very much larger and more ambitious plant for the Tata Works in India, the results of which remain to be seen.