

Oct. 3, 1933.

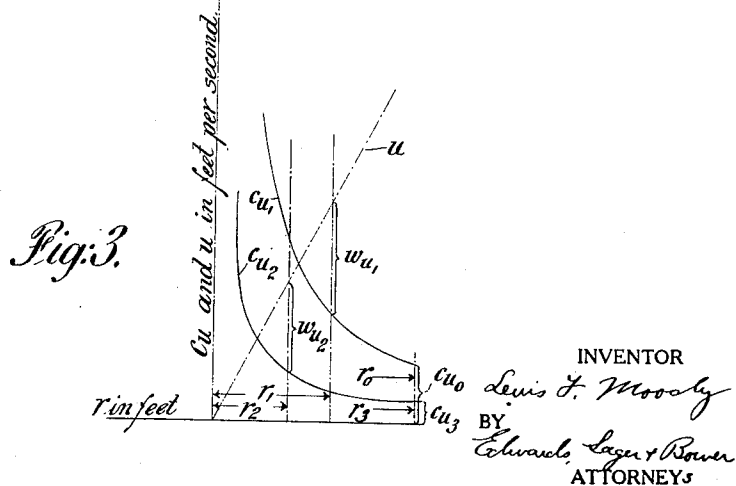
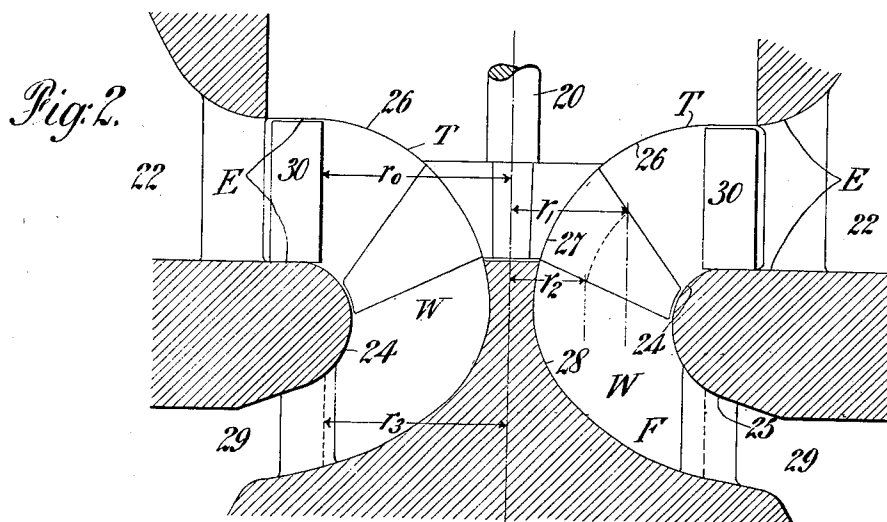
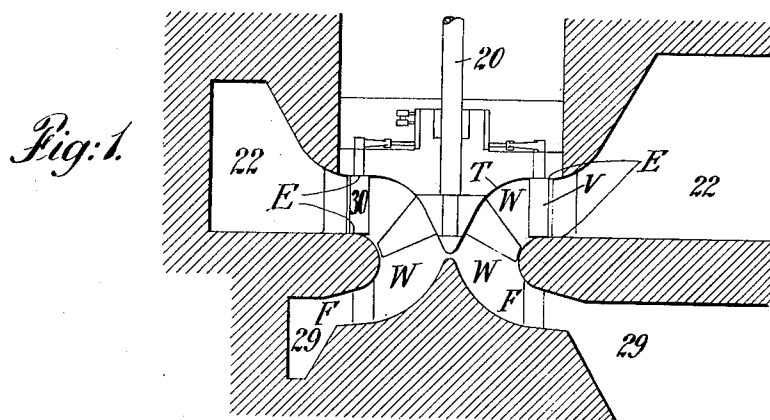
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1,929,099

HYDRAULIC TURBINE

Original Filed April 13, 1920

4 Sheets-Sheet 1



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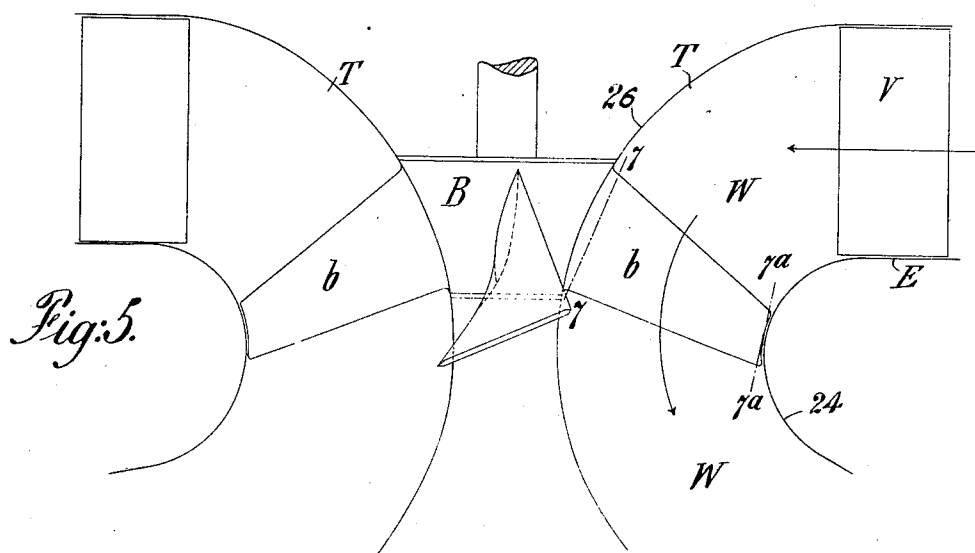
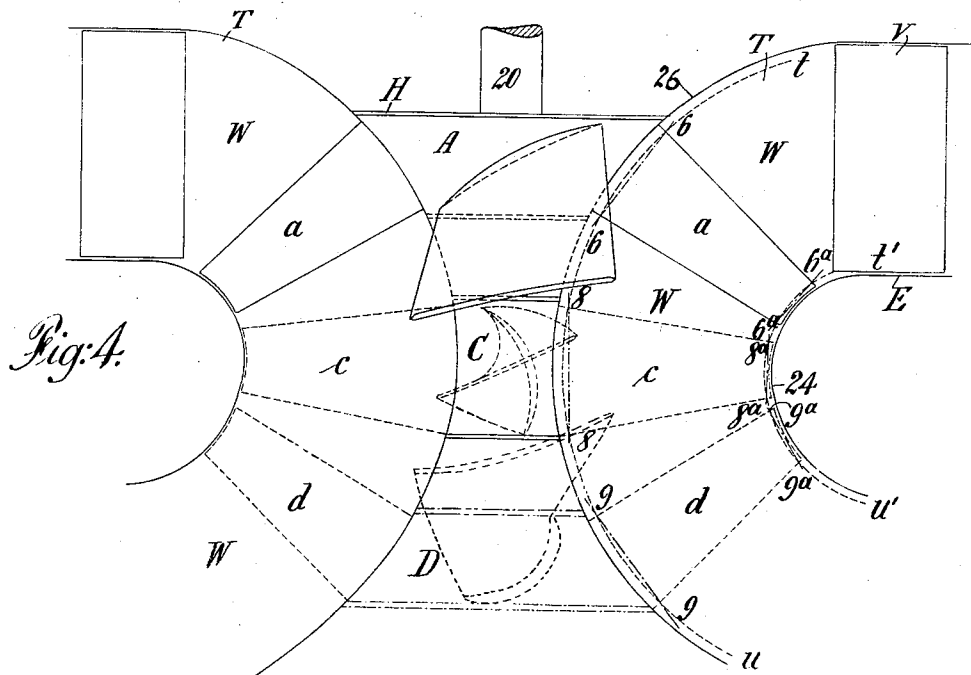
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Fig. 6.

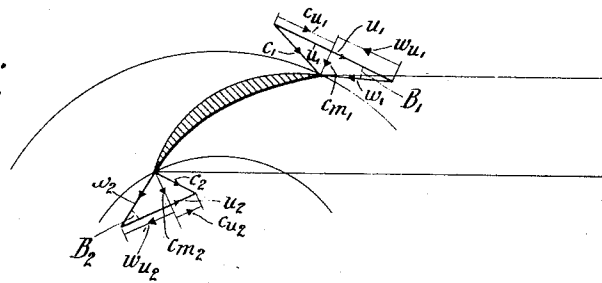


Fig. 6a.

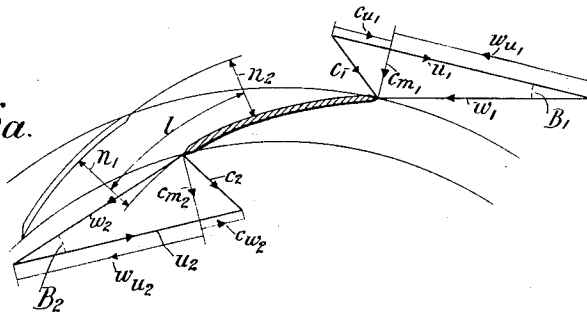


Fig. 7.

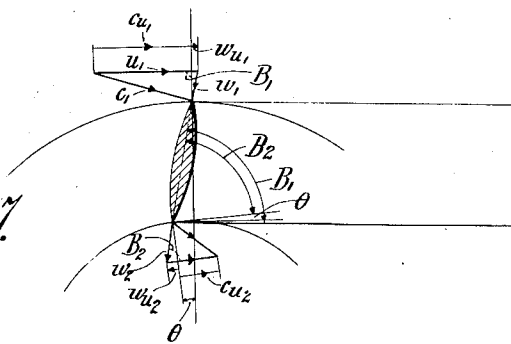
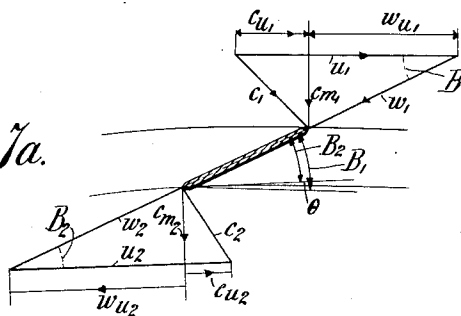


Fig. 7a.



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4 Sheets-Sheet 4

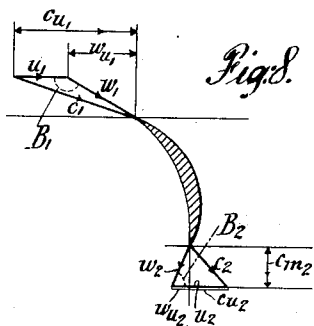


Fig. 8.

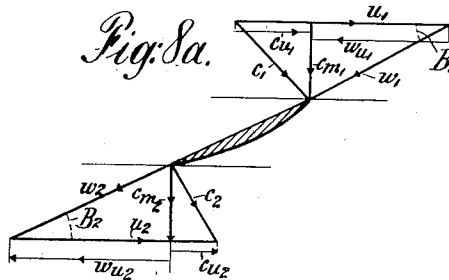


Fig. 8a.

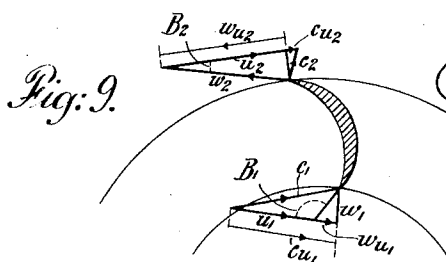


Fig. 9.

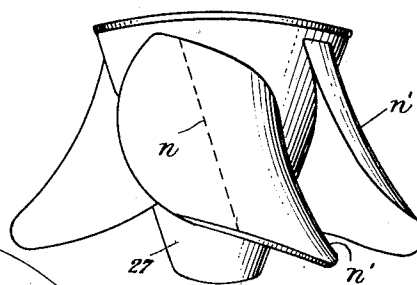


Fig. 11.

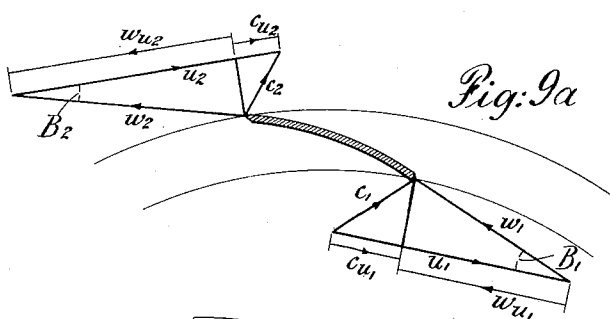


Fig. 9a

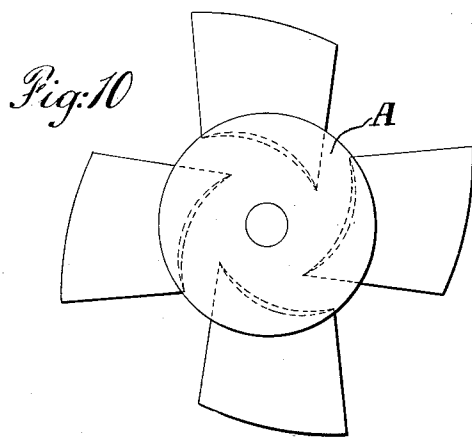


Fig. 10

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UNITED STATES PATENT OFFICE

1,929,099

HYDRAULIC TURBINE

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by mesne assignments, to I. P. Morris & De
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Original application April 13, 1920, Serial No.
373,545. Divided and this application June 18,
1926, Serial No. 116,813. Renewed August 8,
1933

27 Claims. (Cl. 253—118)

This invention relates to hydraulic turbines, and particularly to a turbine having a runner of high specific speed as this term is now generally applied in the art. The chief object of the invention is to provide a turbine in which the water passages and runner cooperate together to attain high specific speed for the runner with high efficiency for every part of the water stream.

A further object of the invention is to provide a water passage adapted to turn the water flow from inward direction to outward without the formation of eddies.

A further object of the invention is to combine with this passage a runner of simply formed blading operating in the stream within said passage at high relative velocity between the blades and the water without causing eddies or high friction losses.

With runners of relatively high rotational speed it is particularly important to avoid eddies and disturbances of the flow and to maintain smooth conditions of flow without sudden changes of curvature of path or of direction or magnitude of velocity, and it is especially important to simplify and smooth out the flow lines and surfaces at the turbine runner where any irregularities are particularly liable to be harmful. In order to keep as small as possible the losses in the water passing through a high speed runner it is desirable that, while maintaining the proper action of the water on the runner blades, the curvature of the blades and the amount of exposed surface should be reduced. While some attempts in this direction have been made, so far as I am aware no definite design has hitherto been evolved securing these results or giving the proper relation between the factors controlling the blade shape and angle.

The manner of carrying out my invention will appear from the following description and the accompanying drawings, in which:

Fig. 1 is a vertical sectional view of a turbine illustrating one embodiment of the invention.

Fig. 2 is a view on enlarged scale of a portion of Fig. 1.

Fig. 3 is a diagram showing the relation of the flow velocities at different points in the water passage.

Figs. 4 and 5 are elevational views illustrating different forms of runners.

Figs. 6 to 9a are diagrammatic views illustrating sections of runner blading, and

Fig. 10 is a plan view of the runner shown in Fig. 4 at A.

Fig. 11 is a perspective of the runner.

In the embodiment of the invention in Fig. 1 the turbine shown is of the vertical shaft type and its waterways contain a water passage W smoothly and continuously curving in the same direction from the radially directed entrance E to the expanding draft tube F without any sudden changes in direction or velocity at any point. For simplicity the entrance is of the radial inflow or Francis type and is provided with inflow guide vanes V which may be fixed or adjustable or both as shown in Fig. 1, and these vanes are set at an inclined position for normal operation so as to give the entering water a whirl around the axis 20 of the runner. The flow from the head water to the entrance space E may be by any convenient intake such as the contracting volute passage 22. The outer wall 24 of the passage W curves smoothly from the entrance E into the axial direction at the center and then continues this curvature back toward the radial direction to merge into the outer wall 25 of the conical expanding draft tube F.

The flow is thus guided first inwardly and then axially and then outwardly in smooth lines of continuously varying curvature, the curvature being at first small, approaching a maximum near the throat or point nearest the axis and then gradually decreasing to the outlet. This continuously curving wall thus avoids the sudden sharp curvature and subsequent straight line design and sometimes the use of reverse curves which has hitherto been characteristic practice in turbines having inward flow guide vanes. The preserving of a gradual change of curvature is particularly important with turbines of high specific speed in which high velocities of flow are used.

The inner wall 26 of the water passage W curves smoothly from the radial toward the axial direction merging with the runner crown 27 and being resumed by the surfaces of the central cone 28 formed in the inner surfaces of the expanding draft tube F from which the outflow may be collected and passed to the tailwater as by discharge passage 29. The inner wall would be spaced from the outer wall so as to give the proper area corresponding to the desired velocity at each point of the passage, and due to the nearness of the inner wall to the axis its central portion may be of nearly constant curvature or have points of higher curvature above and below the throat, but as in the outer wall the curvature will be continuously varying throughout.

Due to the whirl at the entrance caused by

the entrance guide vanes the flow lines through this passage W are spirals first contracting and then expanding. Such a water passage maintains smooth conditions of flow and avoids any sudden change in the distribution of velocities and the consequent formation of eddies, and is consistent with minimum overall dimensions of the turbine. The radial inward direction of the flow is well adapted to advantageous methods of regulation as by the adjustable guide vanes 30 in the entrance space. If successive cross sections of the passage W are taken, each section being taken along a conical surface coaxial with the runner and extending transversely across the flow, that is, substantially at right angles to the central flow lines, the areas of these cross sections near the entrance space E will be greater than the cross sectional areas near the runner, that is, these cross sectional areas will progressively decrease from the entrance space E to the runner and beyond the runner these cross sectional areas then gradually increase from the discharge end of the runner to the final outlet 29, thus in its lower portion providing a draft tube F radially expanding and simultaneously increasing in cross section so as to efficiently regain both the whirling and meridian components of velocity, a meridian component being that component taken in a plane containing the runner axis.

This outward flow passage at discharge provides an efficient diffuser in which the energy of whirl components of flow can be efficiently regained within a limited space; and such a passage enables the overall dimensions of the turbine to be kept a minimum and the whole structure made very compact. A radial outward flow passage is efficient for regaining the velocity head of whirl for the reason that although the radial extent of such a passage may be limited, the actual distance traversed by the whirling elements of the stream is much greater than the length of the passage measured in the cross-section containing the axis, since the actual paths of the stream elements are gradually expanding spirals. Consequently in such a passage the absolute velocity of flow may be reduced at a sufficiently gradual rate to provide high efficiency of conversion of velocity head into pressure-head. The turbine of this invention is designed for a comparatively high velocity of whirl during the passage of the water through the runner, and its reduction in the runner is moderate in comparison with the whirl at entrance to the runner, so that a very considerable amount of whirl still remains at the runner discharge.

This continuously curving vortex form of water passage W thus permits of the efficient use of high components of whirl throughout and such a whirling stream curving gradually in a meridian plane is especially adapted in the installation of this invention to cooperate with a simple form of runner to attain a high specific speed and smooth and efficient conditions of flow.

It being understood that the entrance guide vanes or wicket gates are set at an inclined position for normal operation, so as to give the entering water a velocity of whirl c_{u0} at a radius r_0 , let us call the whirl in the water after leaving the runner c_{u3} at a radius r_3 . This discharge whirl may be considered for simplicity at a position r_3 equal to r_0 (see Fig. 2). All entering streams pass the outflow or inner edges of the guide vanes at radial position r_0 , and all pass

through the r_3 position at discharge; between these points, however, some streams pass close to the axis and some pass at a considerable distance from the axis. For any stream element we can write

$$r_0 c_{u0} - r_3 c_{u3} = 60 \frac{g H e}{2 \pi N}$$

in which:

H=effective head on turbine
e=hydraulic efficiency of turbine
N=rev. per minute of turbine and
g=acceleration of gravity.

If e be made substantially the same for all parts of the turbine, the second member of this equation is a constant for all stream elements, and if r_3 is chosen the same as r_0 , we see that $c_{u0} - c_{u3}$ is the same for all stream elements. If guide vanes of uniform section are used, c_{u0} will be constant and hence c_{u3} is constant. It may also be seen that $r_0 c_{u0}$ represents the torque exerted by the entering water (per unit of mass) and $r_3 c_{u3}$ that of the leaving water, the difference being the torque exerted on the runner. Under the above conditions this is evidently constant for all stream elements and hence the water passing through the portion of the runner nearest the hub must exert upon it just as much torque as that passing through the outermost portion. Since the radius of the portion near the hub is much smaller than that of the outermost portion, there must be a compensating increase in the force exerted by the innermost stream elements to give the desired constant torque.

In the combination of this invention this increase in force can be obtained by a greater deflection of the water passing through the runner; that is, the runner vanes near the hub may be formed to turn the water through a much greater angle than the outermost portions of the vanes. Indeed, in the turbine of this invention if the difference in radius is too great, the innermost vane section if designed for constant torque will result in a "hooked" form of extremely curved shape (see Fig. 8 and the vane formation C in Fig. 4), the entrance edge being inclined backward so as to point in the direction opposite to the runner's rotation, in order to produce sufficient deflection in the water to give the necessary driving force and torque to the vane. Such a hooked form of vane section results in a complicated surface formation and with such a hooked form of vane there is danger of the lines of flow departing from the vane surface and causing eddies and losses.

In accordance with the relations above established, the flow both as to magnitude and direction may be determined at the entrance to and discharge from the runner whatever its position in the passage or the curvature of its edges as viewed in projection, as in Fig. 5. The runner may be placed in any one of various positions, such as A, B, C or D, and the vane angles determined, the blades being inclined at their entrance and discharge edges at an angle coinciding with the relative motion of the water at each point along said edges. For any of these positions A, B, C or D the vane edges may have any one of a wide variety of shapes. In so-called Francis type turbines it has been usual to give the projected vane edges and the transverse elements of the vane surface a pronounced curvature with the object of keeping these edges and elements as nearly normal to the flow lines as possible at all points. Departing from this prac-

the runner blades of this invention are preferably composed of substantially straight line elements n (Fig. 11) which are actually slightly concave as indicated at n' so that a meridian section through the blade is concave on its upper side and convex on its lower side. These elements extend directly across the passage to give the shortest lines from wall to wall and thus reducing the blade area and the consequent friction losses as much as possible and the vane edges as viewed in projection are substantially straight extending directly across the passage. If sections are taken transverse to the meridian sections it is seen from Figs. 3, 4, 6 and 6a that the upper blade surface is convex and the lower surface concave along transverse elements.

In the runner of this invention, therefore, the elements of the vane surfaces and the entrance and discharge edges cut across the flow on the shortest possible lines and produce a simple form of surface avoiding sharp and complicated curvature and resultant eddy losses and maintaining efficient contact with the stream at all points. The blades will in most instances vary from a relatively flat shape at the tip to a relatively curved form at the hub and the relative shapes of the blade surfaces will change according to the position of the blade in the curved water passage W , that is, according as the blade is of the inward, axial or outward flow type.

The runner may, therefore, consistently with the above described design be located at any intermediate portion of the passage W , the change involving, however, a variation in the contour of the runner blade surfaces. Such variation will in certain positions of the runner tend toward relative simplicity in form of the runner surfaces and especially in the diagonal inward flow runner such as A, a (Figs. 4 and 10) or B, b (Fig. 5) will give a particularly advantageous combination, making this type of the runner in many respects preferable.

To compare the characteristics of the turbine for different positions of the runner four typical forms are illustrated in the Figs. 4 and 5 wherein the blading A is of the inward diagonal flow type, B chiefly of axial and slightly radial flow type, C of strictly axial flow type and D of diagonal outward flow type; each runner having four blades. In Figs. 6, 6a, 7, 7a, 8, 8a, 9 and 9a conical or cylindrical sections of these typical vanes are shown on lines 6—6, 6a—6a, 7—7, 7a—7a, etc. with velocity triangles, illustrating the relation of the surface contours to the flow at the different points in the passage W . In these triangles:

c_1 denotes the absolute velocity of the water at entrance into the runner.

c_2 denotes the absolute velocity of the water at exit from the runner.

w_1 denotes the relative velocity of the water at entrance into the runner.

w_2 denotes the relative velocity of the water at exit from the runner.

c_{u1} denotes the absolute velocity of whirl of the water at entrance.

c_{u2} denotes the absolute velocity of whirl of the water at exit.

w_{u1} denotes the relative velocity of whirl of the water at entrance.

w_{u2} denotes the relative velocity of whirl of the water at exit.

u_1 denotes the velocity of the runner at entrance.

u_2 denotes the velocity of the runner at exit.

If dotted lines t , u and t' , u' (Figs. 4 and 5) are

taken to represent the courses of elementary stream particles through the turbine, as shown by circular projection into the meridian plane (the actual courses being spirals contained in surfaces of revolution of which t , u and t' , u' are the generatrices), let us consider the forms of vane sections at hub and tip required for each alternative position of the runner. Calling, as before c_{u0} the absolute whirl of the water at point r_0 at discharge from the guide vanes; c_{u3} the whirl at point 3; and similarly calling c_{u1} the absolute whirl at r_1 , the entrance edge of the vane, and c_{u2} the whirl at r_2 , the discharge edge of the vane, we shall have as already explained $r_0 c_{u0} = r_1 c_{u1}$ and $r_3 c_{u3} = r_2 c_{u2}$; so that $u_1 c_{u1} - u_2 c_{u2} = gHe$.

Hence whenever a stream element enters and leaves the runner at the same radial distance from the axis, as in axial flow runner C, so that $u_1 = u_2$, we shall have c_{u1} greater than c_{u2} and consequently w_{u2} greater than w_{u1} , since $w_{u2} = u_2 - c_{u2}$ and $w_{u1} = u_1 - c_{u1}$; so that

$$w_{u2} - w_{u1} = \frac{gHe}{u_1} = \frac{gHe}{u_2} \quad (100)$$

(See Figs. 8 and 8a). Figs. 8 and 8a are developed cylindrical sections of the vane, on the lines 8—8 and 8a—8a of Fig. 4.

Assuming that in passing through the small space measured in the meridian direction representing the depth of the vane, the meridian component of flow will remain substantially constant, or $c_{m1} = c_{m2}$, approximately, we shall have $\beta_1 > \beta_2$, so that the center line of the vane section should be concave when viewed from the face or driving side and convex when viewed from the back. Hence, the characteristic shape of an axial-flow runner, when properly designed to suit the relative directions of the entering and leaving water, is a concave form when viewed from the face side of the vane. This applies to every vane section where the meridian projection of the flow is purely axial.

In a runner of the outward diagonal flow type, Fig. 4, D, considering the flow on conical sections as shown developed in Figs. 9 and 9a we shall have as before $u_1 c_{u1} - u_2 c_{u2} = gHe$.

Since gHe is a positive quantity the product $u_1 c_{u1}$ must be greater than $u_2 c_{u2}$; and since in an outward-flow runner u_2 is greater than u_1 , c_{u1} must be greater than c_{u2} , and consequently $w_{u2} = u_2 - c_{u2}$ must be greater than $w_{u1} = u_1 - c_{u1}$; (because $u_2 > u_1$ and $c_{u2} < c_{u1}$). Hence, in such a runner, β_1 is greater than β_2 and the vane must be concave when viewed from the face side.

In an inward-flow runner such as A, developed conical sections 6—6 and 6a—6a of which are shown in Figs. 6 and 6a, if u_1 exceeds u_2 by a sufficient amount c_{u1} will be nearly equal to or even less than c_{u2} and consequently w_{u1} will be greater than w_{u2} . Hence β_2 will be exceed β_1 and the vane will be convex when viewed from the face or driving side.

The relations between the velocities at entrance and discharge can be more easily visualized with the help of the diagram, Fig. 3. This diagram shows graphically the variation of c_{u1} and c_{u2} for different values of r by means of two rectangular hyperbolas drawn through the points $r_0 c_{u0}$ and $r_3 c_{u3}$; and also shows by means of a straight line the values of u_1 and u_2 for the same values of r . The differences between u_1 and c_{u1} ; and u_2 and c_{u2} are evidently equal respectively to w_{u1} and w_{u2} , which are given directly by the in-

tercepts between the line of u and the corresponding hyperbola.

As the type of runner is changed from A to C, passing through various intermediate positions such as B (Figs. 5 and 6 and 6a), r_1 and r_2 will gradually approach each other and become equal for runner C. Runner A, as just shown, has vanes convex toward the face, while runner C has vanes convex toward the back. At some intermediate position, such as B, the vane will become flat (Figs. 5, 7 and 7a) and on either side of this position the vane will curve in opposite directions. This flat form of vane will correspond to just enough excess of r_1 over r_2 to give a value of w_{u2} sufficiently greater than w_{u1} so that β_1 will exceed β_2 by the amount θ ; θ being the angle subtended by the vane. (See Figs. 7 and 7a). If the values of r_1 and r_2 correspond to the points of intersection of the hyperbolas with the line of u , w_{u1} and w_{u2} will both be zero, and β_1 and β_2 both equal to 90° ; that is, the vane will be straight and parallel to the axis. This condition will give minimum relative velocity between the vane and the water, the vane velocity being equal to the absolute whirl at both entrance and discharge, but under usual conditions this form of vane would not be the most preferable because not sufficiently strong due to the form of the section.

In order to produce a runner having vanes of simple form and of smooth curvature at all points, it is desirable to avoid any surfaces concave at one place and convex at another, since such reversals of curvature introduce unnecessary complications in the form, are difficult to design and construct, and increase the liability of the actual lines of flow disagreeing with the vane form, with the consequent formation of eddies and loss in efficiency. Such reversal of curvature is found in runners as heretofore constructed. In such runners having complicated surfaces with sudden changes in curvature across the flow lines, any variation of the actual flow lines from those assumed, particularly likely to occur when operating under other than normal conditions of gate and the speed, will result in serious disagreement between the actual vane shape and that required by the flow.

In this invention such values may be selected for r_1 and r_2 at every section (r_1 being greater than r_2 at every section although r_1 and r_2 may be nearly equal at the outermost section) that the vane is either almost completely flat throughout, or slightly convex toward the face at all points. (See runners A and B, Figs. 4, 5, 6, 6a and 7, 7a). For usual conditions a slightly convex face at all sections may be preferred approaching the runner A form, for instance, since by employing such a form it is possible to provide a considerable width of blade where the blade joins the hub (Fig. 10), and to give the blade a moderate inclination at this section, and thus to provide ample strength for the blade, particularly for resisting tangential blows when the vane strikes trash or obstacles carried by the water. Every section of the vane taken along the surface of a cone cutting through the vane in the general direction of flow and having its axis coinciding with the axis of the runner, such for example as the cone generated by revolving the line 7-7 of Fig. 5 about the runner axis will then be a spiral or a curve slightly concave with respect to a point lying in the turbine axis and the entrance edges of the blades will be inclined at an angle coinciding with the relative motion of the water at each point along the edge. It should be understood that in the

description of the blade shape, the shape referred to, unless otherwise specifically pointed out, is that of the central surface midway between the front and back surfaces, which may, of course, be slightly different from the central surface due to the thickness of the metal and the taper toward the edges.

Such a diagonal inward flow runner also permits the blade surfaces to be formed by nearly straight line elements in a very simple manner; and this simplicity is consistent with the maintenance of constant torque at all points across the flow and consequently with the attainment of high efficiency.

The relatively large hub of such a diagonal runner is also particularly desirable, as in the turbine of this invention the tendency of the runner blading is to become less simple in contour in sections approaching the axis since the whirl velocity of the stream lines entering the runner varies inversely with the radial distance of the element from the axis, as shown in Fig. 3. In Fig. 4, for instance, the blade of the axial runner C at its inner portion develops toward an undesirable backward curvature, making it difficult to adhere to the use of straight line elements without departing from the shape required by the entrance and discharge velocities. With the enlarged conical hub H, naturally usable in the diagonal flow portions of the passage W, the runner blades do not approach closely to the axis and complicated reverse curvatures are thus avoided. The variation of curvature for different portions of the runner is therefore kept within moderate limits and the form of the vane section is made favorable to high efficiency at all points.

In this type of turbine the entrance guide vanes direct the flow with radially inward and tangential velocity components around the turbine axis into a transition space in advance of the runner and the flow in this transition space is turned partly toward the axial before entering the runner. The runner at the inner or hub ends of the blades is above the level of the plane of the lower ends of the guide vanes, while the outer ends of the blades are below said plane, and the entrance edges of the blades make acute angles with said plane containing the lower ends of said guide vanes. The entrance edges of the runner blades are thus positioned only a short distance from the discharge edges of the guide vanes 30, just sufficient to permit a smooth gathering and slight turning of the flow. The turning or transition of the flow begun in the transition space is also smoothly continued in the flow through the runner and preferably the runner blades are formed and spaced so that when viewed in a plane perpendicular to the axis there will be open spaces at the outer portions between the discharge edge of one blade and the entrance edge of the next succeeding blade. In the specific embodiment of the invention herein these open spaces extend inward, from the runner periphery, throughout at least the major portion of the blade length or in some cases completely to the hub so that where the open spaces occur over the major extent of the blades, if a line is drawn from the edge of one blade perpendicularly across the lines of flow through the runner, this perpendicular line will not intersect the next adjacent blade, that is, the perpendicular line will fall outside of the adjacent blade. This spacing of the blades reduces their number and correspondingly reduces the frictional area in 150

contact with the flow particularly at the outer portions of the blades where the velocity is highest. The inner portions of the blade, however, toward the hub overlap so that a line from the edge of one vane perpendicularly across the lines of flow will intersect the next adjacent vane, this overlapping providing definite channels of guidance for the inner flow lines with their relatively high degree of whirl and permitting the blades to be strong at their inner portions and strongly connected to the hub so that a shroud ring at the outer ends may be dispensed with.

Furthermore, since the flow through this preferred diagonal runner A, *a* or B, *b* is in a diagonal inward direction between radial and axial, the points of entrance of the various elementary streams are farther from the axis than the corresponding points of discharge. As a result, the points of entrance of the vanes have a greater velocity u_1 than the points of discharge, u_2 , a condition favorable to low relative velocities of the vanes with respect to the water at both points, since as explained above the water possesses a somewhat greater velocity of whirl before entrance into the runner than it does after discharge from the runner.

The diagonal position of the runner blading, while leaving a transition space T at least as wide as the runner blades viewed in meridian plane and sufficient for the whirling flow to collect into a continuous mass and turn from the radial inflow guide vanes V, reduces the length of this transition space and so reduces the velocity of the flow at an earlier point in the water passage, thus reducing the wall area in contact with the high velocity portion of the stream.

It should be borne in mind that the turbine of this invention is particularly adapted to the production of high specific speeds. To this end the water passages and runner mutually contribute and combine together to maintain the efficiency and smooth flow. In the design of the meridian section of the water passage in which the runner operates it is of importance to avoid curves of small radius and rapid changes in curvature, the variation of the curvature of both walls of the passage W being gradual and continuous throughout. The use of walls of gradually varying curvature in the meridian section is of importance in the turbine of high specific speed for the reason that not only are high velocities of whirl employed but high meridian components of velocity are also used.

The turning of the stream in the meridian plane involves a whirling of the water particles in this plane, which is perpendicular to the plane of the whirl previously referred to, which takes place around the turbine axis, that is, in planes perpendicular to the axis. The whirl in the meridian plane may be called a secondary whirl. It results in the setting up of centrifugal pressures increasing from the outer wall toward the turbine axis, and in an accompanying variation of meridian velocities, these velocities being highest near the outer wall and lowest near the axis. These meridian components of velocity are denoted on the diagrams by the symbols c_{m1} and c_{m2} in Figs. 6, 6a, 7, 7a, etc., and it will be noted that at each section the values of c_{m1} and c_{m2} at the section near the hub are smaller than those at the section near the tips of the blades. This variation is due to the centrifugal force of the secondary whirl which increases the pressures near the turbine axis and correspondingly decreases the meridian velocity components.

In the design of the runner of this invention, due account is taken of this variation of meridian velocities; and all harmful effect of the secondary whirl is avoided. If, however, there were sudden variations in curvature of the meridian section of the passage, there would be sudden unavoidable changes in the centrifugal pressures and in the distribution of meridian velocities, conditions which lead to the refusal of the water to follow the contour of the walls, and to the formation of eddies and wasteful disturbances.

Summarizing the operation of the turbine of this invention used for instance with the preferred radial type of inward flow guide vanes and diagonal inward flow runner, the water enters in entrance space E between guide vanes V in streams progressing inward with a tangential whirl. The walls of the water passage W begin a gradual turning of this whirling flow toward the axial direction and provide a free transition space T between the entrance and the runner wherein the flow lines without obstruction collect into a single whirling mass. The gradual turning in a meridian plane of this rapidly whirling flow is continued throughout the water passage W on lines of slowly changing curvature. Due to the high speed of rotation the combination of this invention involves comparatively light torque on the runner blades so that the whirling flow passes down through the runner which rotates rapidly with respect to the stream which is itself rotating. The runner blades glide through the stream with little disturbance and cause only a moderate change in velocity of the flow, which as it leaves the runner still is whirling with considerable velocity. Beyond the runner the water passage W continues the same smooth lines of gradually changing curvature and this curvature at the runner is continuous with that at the entrance end of the draft tube F, the curvature then gradually decreasing toward the discharge end of the tube. The whirling outflow from the runner therefore is consolidated in the free transition space below the runner again forming a smoothly whirling mass which is then gradually decelerated as it passes to the outlet, the particles flowing along naturally expanding spiral lines.

The combination of this invention thus produces simple and determinate flow conditions out of the relative complexity of an inward intake, an axial flow and an outward discharge, bringing all these elements into smooth cooperation with each other; and permits the use of a runner having blades of simple homogeneous curvature from tip to hub, the term homogeneous meaning that the center of curvature continues on the same side of the blade and the curvature does not reverse at any point.

It should not be inferred that the water passage would be of exactly the same design regardless of the position of the runner. It would be of the same general form, but as soon as the preferred position of the runner is selected, the passage would be designed to start the gradual deceleration of velocity at the runner discharge, the cross-sectional areas and the resulting spacing of the outer and inner wall being proportioned accordingly.

The above description includes a general method of design and calculation for the turbine of this invention, and this method as illustrated herein may be applied to a turbine in which the meridian component of flow is in any desired direction. It is recognized that inward flow runners, mixed flow runners, and axial flow run-

ners are all old in the art, and it is not intended to claim any one of these types as representing in itself the present invention.

Runners of high specific speed having heretofore been developed largely by the experimental or "cut-and-try" method, and the absence of an adequate general theory has not permitted such runners to be intelligently altered to any material extent without introducing uncertainties as to the performance to be expected. For example, there has not heretofore been disclosed any general method or design of such axial flow runners of high specific speed by which the design may be altered to give lower or higher speed, or by which the type may be changed from purely axial to a greater or lesser degree of inward or outward flow.

In the turbine of this invention these uncertainties are overcome in avoiding the complicated shape of runner blading which has been used in high specific speed turbines of the prior art, and in eliminating the sources of uncertainty in regard to the fluid friction losses in the runner. In particular some of the causes of uncertainty which are avoided in this invention are the "spoon shaped" curvature of the runner vanes which has heretofore been common, that is, the pronounced curvature of the meridian sections of the runner vanes; also the decided curvature which has been given to the sections of the runner vanes taken in the direction of flow, that is, in conical sections with the elements of the cone extending in the general direction of flow; the use of a runner band or shroud ring introducing a surface having high relative velocity with respect to the water; and in addition the employment of sudden changes of curvature in the water passage has been abandoned.

In the runner of this invention all of the vane sections can be made with only slight curvature in the direction of flow so that the passages between the vanes will be substantially straight. By this means the uncertainties due to lack of knowledge of losses in elbows can be avoided and the loss due to curvature in the passage can itself be eliminated. Moreover, the avoidance of the necessity for deflecting the water through large angles permits the lengths of the vanes to be reduced and their spacing increased, thus reducing the area of the exposed surface as illustrated in the four bladed runners of Figs. 4 to 10. The passages between the runner vanes are, therefore, in the turbine of this invention reduced to short sections of straight conduits for which the fluid losses can be calculated. The blades of the runners of Figs. 4 to 10 are so formed and spaced that open spaces are left between at least the outer portions of the blades as seen in a plan view. At their inner portions the blades are nearer together and overlap, that is, a line at right angles to the lines of flow and extending from the edge of one blade will intersect the adjacent blade.

This application, directed generally to the open type of propeller runner, is a division of the co-pending application of Lewis F. Moody, Serial No. 373,545, filed April 13, 1920 for Hydraulic turbine.

I claim:

1. In a hydraulic turbine of high specific speed the combination of guide vanes directing the flow with radial inward and tangential velocity components with respect to the turbine axis, a runner having blades with outer ends below said vanes and inner ends extending above the lower

ends of said vanes, said blades being formed and spaced to leave throughout at least the major portion of their length open spaces between them when projected on a plane perpendicular to the runner axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, and a vane-free transition space extending between said vanes and said runner blades and bounded on the side toward the axis by a surface of revolution.

2. In a hydraulic turbine of high specific speed the combination of guide vanes directing the flow with radial inward and tangential velocity components with respect to the turbine axis, a runner having unshrouded blades with outer ends below said vanes and inner ends extending above the lower ends of said vanes, said blades being formed and spaced to leave throughout at least the major portion of their length open spaces between them when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, and providing a vane-free transition space between said guide vanes and said runner blades.

3. In a hydraulic turbine of high specific speed the combination of guide vanes directing the flow with radial inward and tangential velocity components with respect to the turbine axis, a runner having less than six blades with outer ends below said vanes and inner ends extending above the lower ends of said vanes, said blades being formed and spaced to leave throughout at least the major portion of their length open spaces between them when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, and providing a vane-free transition space between said guide vanes and said runner blades.

4. In a water turbine a runner comprising a hub and a plurality of blades, said blades being inclined diagonally to the runner axis, and formed and spaced so as to leave throughout at least the major portion of their length open spaces between them when viewed axially and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, and a vane-free transition space bounded by inner and outer surfaces of revolution, the inner surface turning from radial direction toward axial direction to conform in contour to the runner hub.

5. In a hydraulic turbine of high specific speed the combination of guide vanes directing the flow with radial inward and tangential velocity components with respect to the turbine axis, a runner having less than six unshrouded blades with outer ends below said vanes and inner ends extending above the lower ends of said blades, said blades being formed and spaced to leave throughout at least the major portion of their length open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, and

a vane-free transition space between said guide vanes and said runner blades.

6. In a hydraulic turbine of high specific speed the combination of guide vanes directing the flow with radial inward and tangential velocity components with respect to the turbine axis, a runner having unshrouded blades with outer ends below said vanes and inner ends extending above the lower ends of said blades, said blades being formed and spaced to leave throughout at least the major portion of their length open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, a vane-free transition space between said guide vanes and said runner blades, and a draft tube having a relatively long symmetrical portion in comparison with the runner diameter with gradual and continuous enlargement of area so as efficiently to convert velocity head into pressure head.

7. In a hydraulic turbine of high specific speed the combination of guide vanes directing the flow with radial inward and tangential velocity components with respect to the turbine axis, a runner having unshrouded blades with outer ends below said vanes and inner ends extending above the lower ends of said blades, said blades being formed and spaced to leave throughout at least the major portion of their length open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, and a vane-free transition space between said guide vanes and said runner blades bounded by inner and outer surfaces of revolution, the inner surface turning from radial toward axial direction to conform in contour to the runner hub.

8. In a hydraulic turbine of high specific speed the combination of guide vanes directing the flow with radial inward and tangential velocity components with respect to the turbine axis, a runner having less than six blades with outer ends below said vanes and inner ends extending above the lower ends of said vanes, said blades being formed and spaced to leave throughout at least the major portion of their length open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, and providing a vane-free transition space between said guide vanes and said runner blades bounded by inner and outer surfaces of revolution, the inner surface turning from radial toward axial direction to conform in contour to the runner hub.

9. In a hydraulic turbine of high specific speed the combination of a conduit turning from radial to axial and guide vanes directing the flow with radial inward and tangential velocity components with respect to the turbine axis, a runner having a hub tapering from a large diameter at its entrance portion to a small diameter at its discharge portion, and unshrouded blades extending diagonally with respect to the axis and being formed and spaced to leave, throughout at

least the major portion of their length, open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, the inflow edges of said blades intersecting the hub at a point which is radially disposed from the runner axis by a distance slightly greater than one-half the greatest tip radius of the blades.

10. In a high specific speed hydraulic turbine the combination with an intake adapted to direct the flow radially inwardly and impart a whirl to it, of an outlet through which the flow passes outwardly away from the axis and with a whirl, a conduit continuously curving in the same direction and leading from said intake to said outlet, and a turbine runner in said conduit having blades formed and spaced to leave, throughout at least the major portion of their length, open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

11. In a high specific speed hydraulic turbine the combination with an intake adapted to direct the water radially inwardly and impart a whirl to the flow, of adjustable guide vanes for varying said whirl, an outlet through which the flow passes outwardly and with a whirl, a conduit continuously curving in the same direction and leading from said intake to said outlet, a turbine runner in said conduit and spaced from said intake so as to leave a curving transition space between said intake and said runner and having blades formed and spaced to leave, throughout at least the major portion of their length, open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

12. In a high specific speed hydraulic turbine structure the combination with an intake passage and a discharge passage relatively closely spaced to bring said passages into proximity with each other, of a conduit bounded by surfaces of revolution continuously curving in one direction and leading from said intake to said discharge, and a turbine runner in said conduit having blades formed and spaced to leave throughout at least the major portion of their length, open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

13. In a high specific speed hydraulic turbine the combination with an entrance space having an inwardly directed flow, of means for imparting a whirl to said flow, a curving transition space receiving the flow from said entrance space and turning it toward the axial direction, a runner in said flow, having blades formed and spaced to leave throughout at least the major portion of their length, open spaces therebetween when projected on a plane perpendicular to the axis and

the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, and a continuously curving water passage receiving the flow from said runner and turning it gradually toward the radial outward direction in diverging spiral flow lines.

14. In a high specific speed hydraulic turbine the combination with an entrance space having an inwardly directed flow, of means for imparting a whirl to said flow, a spreading draft tube adapted to decelerate the whirling outflow on expanding spiral lines, a water conduit of continuous curvature guiding the flow from said entrance space to said draft tube, and a runner in said passage having blades formed and spaced to leave, throughout at least the major portion of their length, open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

15. In a high specific speed turbine the combination with a curving water conduit, of means for directing the flow into said passage with a whirl, and a runner in said passage spaced from said means and comprising vanes having substantially straight line elements extending across said passage and formed to receive a uniform torque from the whirling flow at different points across said passage, said vanes having blades formed and spaced to leave, throughout at least the major portion of their length, open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

16. A runner for a high specific speed hydraulic turbine having diagonal blades with homogeneously curved driving surfaces convex away from the runner axis and back surfaces concave to the runner axis, said blades being formed and spaced to leave, throughout at least the major portion of their length, open spaces therebetween when projected on a plane perpendicular to the axis and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

17. The combination as set forth in claim 9 wherein said conduit has its inner surface formed as a curved surface of revolution to provide a transition space and said surface being substantially continuous with the contour of the runner hub, so as to turn the water gradually and smoothly.

18. The combination as set forth in claim 2 wherein the transition space is bounded on the side toward the runner axis by a curved surface of revolution substantially continuous in contour with the runner hub.

19. A high specific speed hydraulic turbine propeller runner comprising a hub having blades extending outwardly therefrom with their radial elements inclined to a horizontal plane, each of said blades having its upper surface concave along the radial elements thereof and convex in a direction transverse thereto, said blades in plan view being non-overlapping throughout at least a major portion of their length and the blades also

being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

20. A high specific speed hydraulic turbine propeller runner comprising a hub having blades extending diagonally therefrom, the upper surface of said blades being concave along one element and convex along an intersecting element, said blades in plan view being non-overlapping throughout at least a major portion of their length and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

21. A high specific speed hydraulic turbine propeller runner comprising a hub having blades extending outwardly therefrom, each of said blades having at least a portion thereof concave along its outwardly extending element and being convex over at least a portion of its surface when taken along a transverse element, said blades in plan view being non-overlapping throughout at least a major portion of their length and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

22. The combination in a high specific speed hydraulic turbine, comprising a conduit turning from radial to axial, guide vanes for whirling the inflow through said radial portion, a runner spaced from said vanes to form a transition space which is bounded on its inner surface by the conduit wall formed as a curved surface of revolution continuous with the runner hub, said runner having blades which in meridian section are concave on top and in sections transverse thereto are convex on top, said blades in plan view having open spaces between them throughout at least a major portion of their length and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

23. The combination in a high specific speed hydraulic turbine comprising a runner having a hub carrying blades which are relatively flat in the direction of flow thereover, and which in plan view have their adjacent edges spaced so as to leave, throughout at least the major portion of their length, open spaces of material width and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, means forming a passage including a vane-free transmission space for conducting flow to said runner, guide vanes adapted to impart whirl to the inflow, and an annular draft tube having a central core terminating at its upper end substantially adjacent said hub, said core having a smaller diameter at an intermediate point of its length than at a point adjacent to the runner hub.

24. The combination in a high specific speed hydraulic turbine comprising a passage turning from a radial to an axial direction, guide vanes adapted to impart whirl to the inflowing fluid, and an unshrouded runner disposed in said passage in spaced relation to said vanes to form a transition space of substantially constant volume throughout turbine operation, said runner having a relatively small number of diagonal blades, the

adjacent edges of successive blades being disposed, throughout at least the major portion of the length of said blades, a substantial distance from a common meridian plane so as to form in plan view open spaces between said adjacent edges.

25. The combination in a high specific speed hydraulic turbine comprising a passage turning from a radial to an axial direction, guide vanes for whirling the inflowing fluid, and an unshrouded runner disposed in said passage in spaced relation to said vanes to form a transition space of constant volume throughout turbine operation, said runner having a relatively small number of diagonal blades which are relatively flat in the direction of flow thereover and which throughout at least the major portion of the adjacent edges of successive blades are disposed a substantial distance from a common meridian plane so as to form in plan view open spaces between said adjacent edges, and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade.

26. The combination in a high specific speed hydraulic turbine comprising a passage turning from a radial to an axial direction, guide vanes for whirling the inflowing fluid, and an unshrouded runner disposed in said passage in spaced relation to said vanes to form a transition space of constant volume throughout turbine operation, said runner having a relatively small number of diagonal blades which throughout at least the major portion of the adjacent edges of successive

blades are disposed a substantial distance from a common meridian plane so as to form in plan view open spaces between said adjacent edges and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, said blades also being relatively flat in the direction of flow thereover, and being disposed at least adjacent the blade tips, in a more nearly horizontal than vertical position.

27. The combination in a high specific speed propeller type hydraulic turbine comprising, a passage turning from a radial to an axial direction through a transition space, guide vanes for whirling the inflowing fluid, and an unshrouded runner disposed in said passage in spaced relation to said vanes to form said transition space, said runner having a relatively small number of diagonal blades which throughout at least the major portion of the adjacent edges of adjacent blades are disposed a substantial distance from a common meridian plane so as to form in plan view open spaces between said adjacent edges and the blades also being arranged so that throughout said major portion a line extending from the edge of one blade, perpendicular to the flow through the runner, will fall outside of the adjacent blade, and said blades also being inclined so as to form at their inner portion an overlapping relation between the same when measured in a direction normal to the flow through said inner portion.

LEWIS FERRY MOODY.

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