Design, Modeling & Analysis of Pelton Wheel Turbine Blade

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Abstract— A Pelton-wheel impulse turbine is a hydro mechanical energy conversion device which converts gravitational energy of elevated water into mechanical work. This mechanical work is converted into electrical energy by means of running an electrical generator. The Pelton turbine was performed in high head and low water flow, in establishment of micro-hydroelectric power plant, due to its simple construction and ease of manufacturing. To obtain a Pelton hydraulic turbine with maximum efficiency during various operating conditions, the turbine parameters must be included in the design procedure. Here all design parameters were calculated at maximum efficiency by using MATLAB SOFTWARE. These parameters included turbine power, turbine torque, runner diameter, runner length, runner speed, bucket dimensions, number of buckets, nozzle dimension and turbine specific speed. The main focus was to design a Pelton Turbine bucket and check its suitability for the the pelton turbine. The literature on Pelton turbine design available is scarce; this work exposes the theoretical and experimental aspects in the design and analysis of a Pelton wheel bucket, and hence the designing of Pelton wheel bucket using the standard rules. The bucket is designed for maximum efficiency. The bucket modelling and analysis was done by using SOLIDWORKS 2015. The material used in the manufacture of pelton wheel buckets is studied in detail and these properties are used for analysis. The bucket geometry is analysed by considering the force and also by considering the pressure exerted on different points of the bucket. The bucket was analysed for the static case and the results of Vonmises stress, Static displacement and Factor of safety are obtained.

Key words: Hydro Power Plant, Pelton Wheel Turbine Blade

I. INTRODUCTION OF HYDRO POWER PLANT

Hydro power plants use the potential energy of water stored in a reservoir to operate turbines. The turbines are connected to large generators, and can operate on varying volumes of water to adapt to changing demand for electricity.

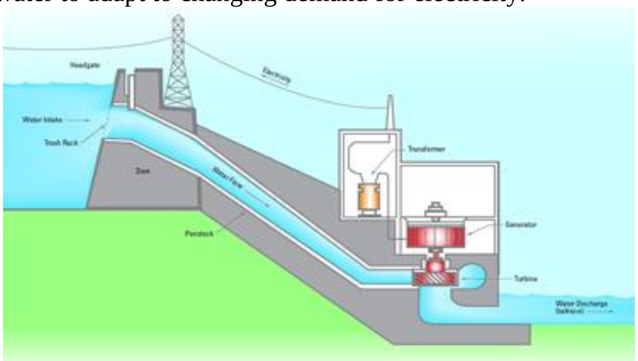

Fig. 1: Hydro Power Plant

Power system mainly contains three parts namely generation, transmission and distribution. Generation means how to generate electricity from the available source and there are various methods to generate electricity but in this article we only focused on generation of electricity by the means of hydro or water (hydro power plant). As we know that the power plant is defined as the place where power is generated from a given source, so here the source is hydro that's why we called hydro power plant.

II. TURBINE DEFINITION

Hydraulic turbine can be defined as a rotary machine, which uses the potential and kinetic energy of water and converts it into useful mechanical energy.

Hydraulic or water Turbines are the machines which use the energy of water (hydropower) and convert it into mechanical energy. In general a water turbine consists of a wheel called runner (or) rotor, having a number of specially designed vanes or blades or buckets. The water processing a large amount of hydraulic energy when strikes the runner, it does work on the runner and causes it to rotate. The mechanical energy so developed is supplied to the generator coupled to the runner, which then generates electrical energy.

The selection of the best turbine for any Particular hydro site depends upon the site characteristics, the dominant ones being the head and flow available. Selection also depends on the desired running speed of the generator or other device loading the turbine.

A. *Types of Turbine*

Turbines are also divided by their principal of operation and can be either impulse turbines or reaction turbines.

1) *Reaction Turbine*

The rotating element (or 'runner') of the reaction turbine is fully immersed in water and is enclosed in a pressure casing. The runner and casing are carefully engineered so that the clearance between them is minimized. The runner blades are profiled so that pressure differences across them impose lift forces, similar to those on aircraft wings, which cause the runner to rotate.

2) *Impulse Turbine*

In contest an impulse turbine runner operates in air, driven by a jet (or jets) of water. And the water remains at atmospheric pressure before and after making contact with the runner blades. In this case a nozzle converts the pressurized low velocity water into a high speed jet. The runner blades deflect the jet so as to maximize the change of momentum of water, and hence maximize the force on the blades. The casing of an impulse turbine is primarily to control splashing because its interior is at atmospheric pressure, impulse turbines are usually cheaper than reaction turbines because there is no need for a specialist pressure casing, nor for carefully engineered clearances. But they are also only suitable for relatively high heads. There are three types of impulse turbine as follow.

Pelton wheel The Pelton wheel is an impulse type water turbine. It was invented by Lester Allan

Pelton in the 1870s. The Pelton wheel extracts energy from the impulse of moving water, as opposed to water's dead weight like the traditional overshot water wheel. Many variations of impulse turbines existed prior to Pelton's design, but they were less efficient than Pelton's design. Water leaving those wheels typically still had high speed, carrying away much of the dynamic energy brought to the wheels. Pelton's paddle geometry was designed so that when the rim ran at ½ the speed of the water jet, the water left the wheel with very little speed; thus his design extracted almost all of the water's impulse energy which allowed for a very efficient turbine.

B. *Runner and Buckets*

Runner consists of a circular disc on the periphery of which a number of buckets evenly spaced are fixed. The space of the buckets is of a double hemispherical cup or bowl. Each bucket is divided into two symmetrical parts by dividing wall which is known as Splitter. The Splitter divides the jet into two equal parts. The buckets are shaped in such a way that the jet gets deflected through 160° or 170°. The buckets are made of cast iron, cast steel bronze or stainless steel depending upon the head at the inlet of the turbine

Fig. 2: Runner and Buckets

III. DESIGN OF PELTON TURBINE

A. *Preparing the Site Data of Power Plant*

This involves the calculations and measuring the net head and the water flow rate.

1) *Calculation of the net head (H_n):*

$$H_n = \mathrm{Hg} - \mathrm{H}_{t_1}$$

For Micro hydro Power plant, assume H_g = 50 m

$$\mathrm{H}_{t_1} = 0.06 * \mathrm{Hg} = 3\ \mathrm{m}$$

$$H_n = 47\ \mathrm{m}$$

2) *Calculation of the turbine input power (Pti)*

The electrical input Power to the turbine in (Watt) can be calculated as:

$$\mathrm{P_{ti}} = \rho * g * C_n^2 * H_n * Q_t\ (\mathrm{Watt})$$

$$\mathrm{P_{ti}} = 44.285\ \mathrm{kw}$$

3) *Calculation of the turbine speed (N)*

The turbine Speed Can be Calculated as:

$$N = N_s * {H_n^{5/4}}\Big/{\sqrt{\mathrm{P_{ti}}}}$$

$$N = 620\ rpm$$

4) *Calculation of the runner circle diameter (D_r)*

The water jet through nozzle has a velocity (V_j) in $(m.s^{-1})$ can be calculated as:

$$V_j = C_n * \sqrt{2 * g * H_n} \qquad (m.s^{-1})$$

$$V_j = 29.75\ {}^{m}/_{s}$$

The runner tangential Velocity (V_{tr}):

$$V_{tr} = w * R_r = \pi N D_r/60 \qquad (m.s^{-1})$$

Also the runner tangential Velocity can be given as:

$$D_r = 38.60 * \sqrt{\frac{H_n}{N}}$$

$$D_r = 0.426\ m$$

5) *Calculation of nozzle dimensions*

The water flow rate through each nozzle (Q_n) can be calculated as:

$$Q_n = V_j * A_j \qquad (m^3.s^{-1})$$

Nozzle Area (A_j) can be calculated as:

$$A_j = \pi * Dj^2/4 = 3.36 * 10^{-3}\ \ m^2$$

$$Q_n = 0.01\ \frac{m3}{s}$$

The Nozzle Length can be calculated as:

$$L_n = {D_{pn} - D_j}\Big/{\tan(\beta)}$$

$$L_n = 0.270\ m$$

The distance between the nozzle and runner should be 5% of the runner circle diameter plus an extra (3) mm clearance to account for emergency deflectors as:

$$X_{nr} = 0.05 * D_r + D_t$$

$$X_{nr} = 0.0243\ m$$

Clearance between the nozzle& buckets is:

$$X_{nb} = 0.625 * D_r$$

$$X_{nb} = 0.266\ m$$

6) *Calculation of Bucket Dimensions*

The bucket axial width can be calculated as:

$$B_w = 3.4 * D_j$$

$$B_w = 0.22\ m$$

The bucket radial length can be calculated as:

$$B_t = 3 * D_j$$

$$B_t = 0.195\ m$$

The bucket depth can be calculated as:

$$B_d = 1.2 * D_j$$

$$B_d = 0.078\ m$$

The number of buckets can be calculated as:

$$N_b = 15 + {D_r}\Big/{2 * D_j}$$

$$N_b = 19$$

The radius of bucket centre of mass to centre of runner was given:

$$R_{br} = 0.47 * D_r$$

$$R_{br} = 0.2\ m$$

The bucket Volume was given as:

$$V_b = 0.0063 * D_r^3 \qquad (m^3)$$

$$V_b = 4.87 * 10^{-4}\ \ m^3$$

7) *Deflector Design*

The force in each deflector can be calculated as:

$$F_d = \rho_w * Q_n * V_j$$

$$F_d = 2975\ N$$

The required force in each deflector was given as:

$$F_{dr} = F_d * S.F$$

$$F_{dr} = 7437.5\ N$$

8) *Calculation of Maximum Turbine Efficiency*

The input power to the turbine can be calculated as:

$$P_{ti} = \frac{\rho_w * Q_t * V_j^2}{2}$$

$$P_{ti} = 44.253\ KW$$

The power output developed by the turbine was given as:

$$P_{to} = \rho_w * Q_t * V_{tr} * [(V_j - V_{tr})(1 + \Psi * \mathrm{Cos}(\Theta))]$$

$$P_{to} = 42.855\ \mathrm{kW}$$

The turbine hydraulic efficiency can be calculated as:

$$n_{th} = \frac{P_{to}}{P_{ti}}$$

$$n_{th} = 96.80\ \%$$

For Maximum hydraulic turbine efficiency:

$$n_{th(Max)} = \frac{[1 + \Psi * \mathrm{Cos}(\Theta)]}{2}$$

$$n_{th(Max)} = 97.33$$

IV. WITH THE HELP OF MATLAB PROGRAMMING WE HAVE ACHIEVED TWO TABLES FOR TWO DIFFERENT CONDITIONS

Hg	**Pto (Kw)**	**η (%)**	**T (N.m)**	**N (r.p.m)**	**N_S**	**nb**
50	43	96.9	660	620	33.5	19
60	51.5	96.9	722	680	32	19
70	60	96.9	779	735	31	19
80	68.5	96.9	832	787	30	19
90	77.2	96.9	882	835	29	19
100	85.8	96.9	930	881	28.3	19
110	94.3	96.9	974	925	27.7	19
120	103	96.9	1016	967	27	19
130	111.5	96.9	1057	1007	26.6	19
140	120	96.9	1097	1045	26	19

Table 1: The Pelton Turbine at Maximum Efficiency and Constant Flow Rate (Qt =0. 1 M^3.S-1)

Hg	Q_t ($m^3.s^{-1}$)	P_{to} (Kw)	T_t (N.m)	η (%)	N (r.p.m)	N_S	nb
(50)	0.1	43	660	96.9	620	33.	19
	0.2	85.8	1320	96.9	620	47.	19
	0.3	129	1980	96.9	620	58	19
	0.4	171.5	2640	96.9	620	67.	19
(60)	0.1	51.5	722	96.9	680	32	19
	0.2	103	1444	96.9	680	45.	19
	0.3	154.4	2167	96.9	680	55.	19
	0.4	206	2889	96.9	680	64.	19

Table 2: Design Parameters of the Pelton Turbine At Maximum Efficiency And Constant Gross Head

V. GENERATED GRAPHS

A. Graph for Constant Flow Rate (condition '1'):

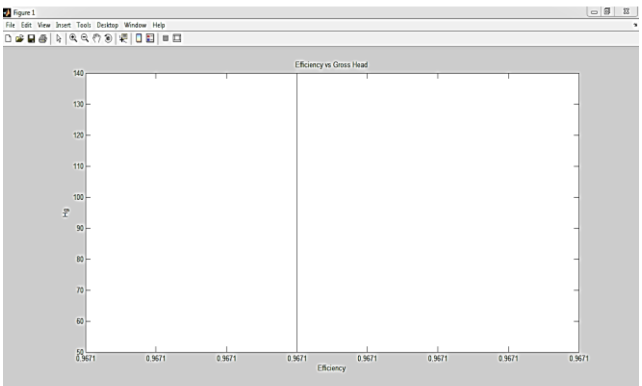

Fig. 3: Efficiency vs. Gross Head

B. Graph for Constant Head (condition '0'):

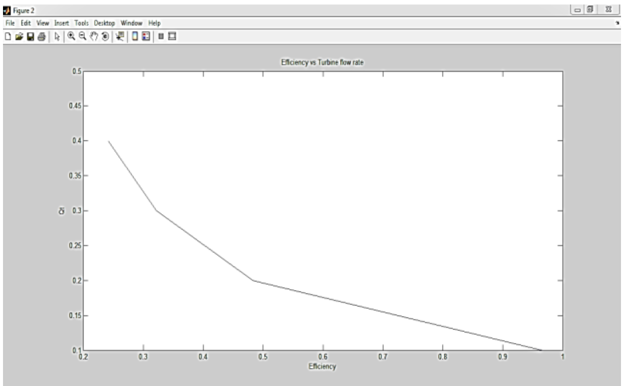

Fig. 4: Efficiency vs. Turbine Flow Rate

VI. MODELLING OF PELTON TURBINE BUCKET IN SOLIDWORKS

SOLIDWORKS (originally Solid Works) is solid modelling CAD (computer-aided design) software that runs on Microsoft Windows and has been produced by Dassault Systems SOLIDWORKS Corp., a subsidiary of Dassault Systems, S. A. (Velizy, France) since 1997. SOLIDWORKS is currently used by over 2 million engineers and designers at more than 165,000 companies worldwide. Solid Works 3D CAD software allows designing and assembling the parts in a better way.

A. Material Properties

For the industrial manufacturing of the pelton wheel turbines the material mainly used is CA6NM. This is a combination of iron, chromium, nickel, and molybdenum which is hardened by heat treatment. This material has very high tensile strength and impact strength. This is not corrosive and thus it is used mainly in constructing structures formed in water. A major application of the alloy has been in large hydraulic turbine runners for power generation.

Property	**Value**
Density	1695 kg/m^3
Young's Modulus	$1.9995*10^5$
Poisson's ratio	0.27
Bulk Modulus	$1.4489*10^{10}$
Shear modulus	$7.872*10^{10}$
Yield Strength	689.43 Mpa
Ultimate Strength	827.37Mpa

Table 3: Major Material Properties

B. Solid works Model of Pelton Turbine Bucket

From all the above calculated parameters and some standard parameters the modeling of the bucket is done using Solidworks 2015.

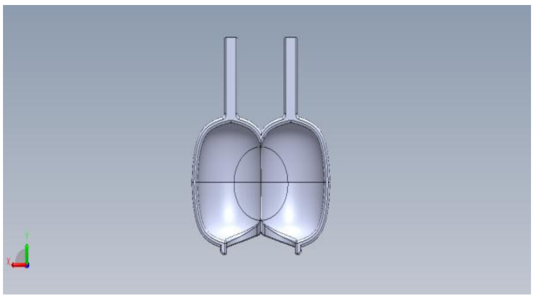

Fig. 5: Bucket 3D Models

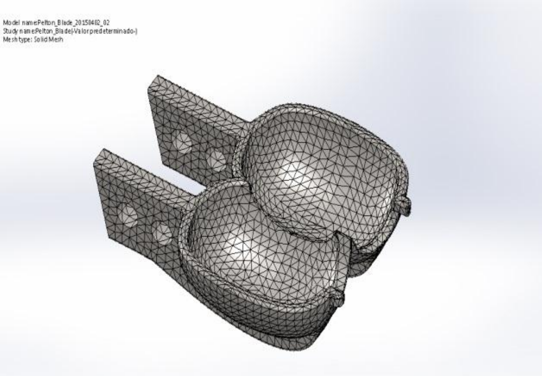

Fig. 6: Bucket Solid Mesh Model

VII. ANALYSIS OF PELTON TURBINE BUCKET

In engineering field the analysis of component can be done in various ways like static, dynamic, fluid interactions etc. depending up on application. Here the analysis can be done based on linear static analysis. During the analysis various assumption were taken. The following is the assumptions:

1) Linearity Assumption
2) Input for Linear Static Analysis
3) The bucket is stationary
4) The bucket profile is uniform
5) Effects of external forces are negligible
6) The fixed at its arm acts similar to a cantilever beam

VIII. ANALYSIS RESULT

In the analysis of bucket various plot is being generated which shown in below The bucket is operated at a head of 50 m and the mass flow rate is 0.1 m^3/s , the first impact force on the splitter is given by F= 153.864 KN.

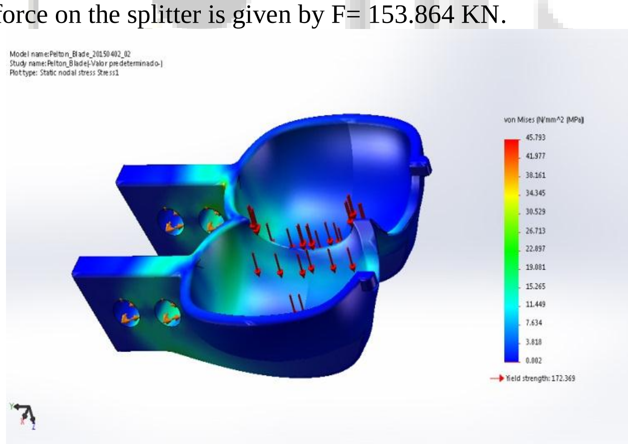

Fig. 7: Vonmises Stress

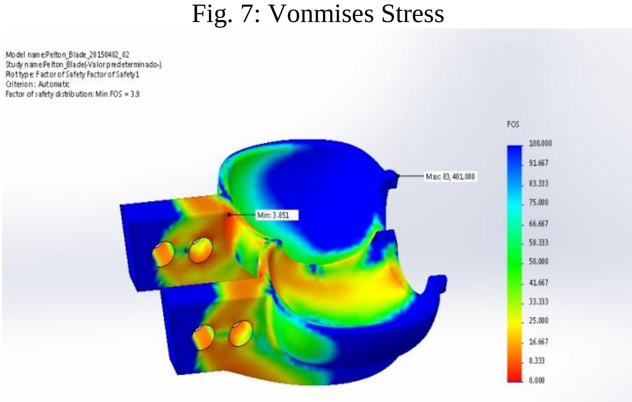

Fig. 8: Factor of safety

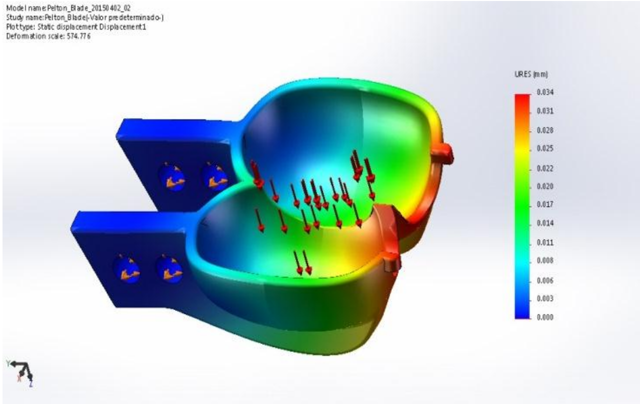

Fig. 9: Displacement analysis

IX. RESULT & DISCUSSION

A. Result of MATLAB Programming

The design calculations of the Pelton turbine were implemented by a Matlab Simulink computer program. Table (1) shows the design parameters of the Pelton turbine with constant flow rate (Q = 0.1 m^3.s-1) and variable gross head of the plant site (Hg= 50 to 140 m), while table (2) shows the same turbine parameters at constant head (Hg = 50 to 60 m) with variable water flow rate (Q = 0.1 to 0.4 m^3.s-1) of the site. Figure (3) shows the variation of runner to nozzle diameter ratio with specific speed at different values of water flow rate, while in figure (4) shows the variation of the same ratio with the nozzle length.

From these results, the turbine maximum efficiency was found to be 97% constant. In case of variable head, all the design parameters were varied with head except of number of runner buckets and runner diameter, while in a variable flow rate all the design parameters were constant except of turbine power, specific speed and nozzle length.

B. Result of Modeling and Analysis

After modelling and analysis of the pelton turbine bucket, the calculated load is 153.684 KN, and impact due to this load on the bucket is described here.

Factor	Maximum	Minimum
Von mises Stresses(N/mm^2)	45.793	0.002
Factor of safety	83401.000	3.851
Displacement	0.034	0.000

Table 4: Analysis Result

X. CONCLUSIONS

The Pelton turbine is suitable for installing small hydro-electric power plants in case of high head and low water flow rate. A complete design of such turbines has been presented in this paper based on theoretical analysis and some empirical relations. The maximum turbine efficiency was found to be 97% constant for different values of head and water flow rate. The complete design parameters such as turbine power, turbine torque, turbine speed, runner dimensions and nozzle dimensions are determined at maximum turbine efficiency using the MATLAB software.

The bucket model is designed according to the calculated parameters and the analysis is done for various parameters in SOLIDWORKS. From the analysis result the FOS achieved is 3.5 so the design model is safe. The

Maximum stress produced by water jet is about 45 N/mm^2 which can be easily withstand by the bucket material (SS316 THE MAXIMUM STRESS CAPACITY = 172.36 N/mm^2)

ABBREVIATION (NOMENCLATURE)

Ab	Peripheral area of penstock (m^2)
Aj	Jet or nozzle cross-sectional area (m^2)
Ap	penstock cross-sectional area (m^2)
Ar	River or steam cross-sectional area (m^2)
Bd	Bucket depth (m)
Bl	Bucket radial length (m)
Bw	Bucket axial width (m)
Cn	Nozzle (jet) discharge coefficient (≅ 0.98)
Dj	Jet or nozzle diameter (m)
Dpn	Diameter of penstock connected to the nozzle
Dpt	Diameter of penstock connected to the turbine
Dr	Runner (wheel) circle diameter (m)
Dt	Deflector thickness (m)
Fc	Friction factor acted upon by bearings (≅1.2)
Fd	Deflector force (N)
Fdr	Required deflector force (N)
g	Gravity acceleration constant (9.81 m.s-2)
Hg	Gross head (m)
Hn	Net head (m)
Hs	Surge head (m)
Ht	Total head (m)
Htl	Total head loss (m)
Kd	Drag coefficient
Kwm	Bulk water modulus ($2.1*10^9$ $N.m^{-2}$)
Lab	Length of bucket moment arm (m)
Ln	Nozzle length (m)
Lpt	Length of penstock between intake and turbine
Mb	Mass of bucket (Kg)
Mp	Modulus of penstock material
nb	Number of buckets
nj	Number of turbine nozzles
np	Manning factor of penstock
N	Turbine (runner) speed (r.p.m)
Nr	Turbine run-away speed (r.p.m)
Ns	Turbine specific speed
Pti	Turbine input power (watt)
Pto	Turbine output power (watt)
Qn	Nozzle flow rate (m3.s-1)
Qt	turbine flow rate (m3.s-1)
Rbr	Radius of bucket center of mass to runner center
Rd	Radius of deflector arm (m)
Rr	Radius of runner (m)
S.F	Safety factor to prevent water hummer effect (>
tp	Thickness of penstock (m)
tpe	Effective thickness of penstock (m)
tsp	Tensile strength of penstock material (N.m-2)
Td	Deflector torque (N.m)
Tdr	Required deflector torque (N.m)
Tt	turbine torque (N.m)
Vb	Volume of bucket (m3)
Vj	Water jet velocity (m.s-1)
Vr	River velocity (m.s-1)
Vtr	Runner tangential velocity (m.s-1)
Vw	Pressure wave velocity (m.s-1)
x	Ratio of runner tangential velocity to jet velocity
Xnb	Distance between bucket and nozzle (m)
Xnr	Distance between nozzle and runner (m)
ΔV	Change in velocity of penstock (m.s-1)

GREEK SYMBOLS

β	Nozzle tapper angle (degrees)
ψ	Bucket roughness coefficient (0.98)
Θ	Deflection angle between bucket and jet (160° to 170°)
ρ_a	Air density (1.23 $Kg.m^{-3}$)
ρ_m	Density of bucket material ($Kg.m^{-3}$)
ρ_w	Water density (1000 $Kg.m^{-3}$)
ω	Runner velocity ($radian.sec^{-1}$)
ω_r	Runner run-away velocity ($radian.sec^{1}$)
η_t	Total turbine efficiency
η_{th}	Turbine hydraulic efficiency
η_{tm}	Turbine mechanical efficiency
η_{tw}	Turbine windage efficiency

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