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Design of High Efficiency Cross-Flow Turbine for Hydro-Power Plant

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***Abstract:** The cross-flow hydraulic turbine was gaining popularity in low head and small water flow rate, in establishment of small hydro-power plant, due to its simple structure and ease of manufacturing in the site of the power plant. To obtain a cross-flow turbine with maximum efficiency, the turbine parameters must be included in the design. In this paper all design parameters of cross-flow turbine were calculated at maximum efficiency. These parameters include runner diameter, runner length, runner speed, turbine power, water jet thickness, blade spacing, number of blades, radius of blade curvature, attack angle and the blade and exit angles.*

***Keywords:** Cross-flow turbine, hydro-power plant, design parameters, maximum efficiency.*

I. INTRODUCTION

Hydro-power was considered as one of the most desirable source of electrical energy due to its environmental friendly nature and extensive potential available through out the world. Within the scope of hydro-electric power, small power plants have gained much attention in recent years.

Several small hydro-power schemes have been proposed and successfully implemented, which include radial, axial, and propeller type turbines. Nowadays, the cross-flow hydraulic turbine is gaining popularity in low head and small water flow rate establishments, due to its simple structure and ease of manufacturing in the site of the power plant. The cross-flow turbine is composed of two major parts, the runner and the nozzle . the runner was a circular rotor with two side walls to which the blades are fixed along the periphery of the turbine. The cross-section of the blades was circular with specific radius of curvature. The nozzle directs the water flow into the runner at a certain attack angle. Typically components of a cross-flow turbine were shown in figure **(1)**. The water jet leaving the nozzle strikes the blades at first stage. The water exits the first stage and was crossed to the second stage inlet after exiting the runner completely. Some of water was entrained between the turbine stages and does not contribute to the energy generation. One of the major design considerations in cross-flow turbine was to minimizing this undesirable uncrossed water flow in order to achieve maximum efficiency [1,2].

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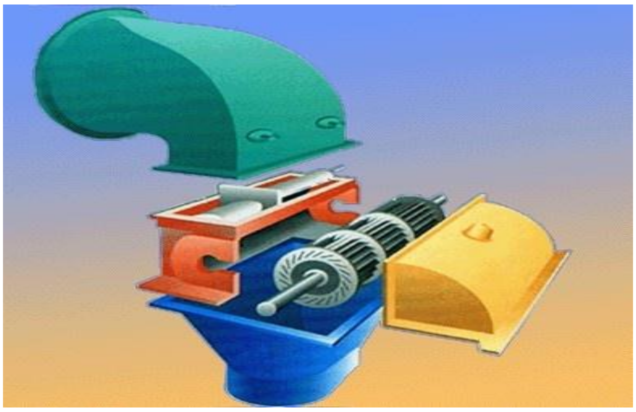

Figure (1) Typical components of cross-flow turbine

The efficiency of the cross-flow turbine was dependent on several design parameters. These include runner diameter, runner length, runner speed, turbine power, water jet thickness, blade spacing, number of blades, radius of blade curvature, attack angle and the blade and exit angles. Since the advent of cross-flow turbines, much advancement has been made in its design through experimental studies and research. Some of published works were presented in references [3-8]. In reference [3], a complete design procedure has been presented based on the theory of cross-flow turbine given in reference [2], but the results are completely anomaly due to a mistake was happen in the transforming British units into metric units, specially in the runner speed equation ($N = 2 * \sqrt{H}/D$), which was a mistake, and the right equation was ($N = 22 * \sqrt{H}/D$), in British units. In this paper the design parameters in metric units were calculated at maximum efficiency of the cross-flow turbine using the Matlab Simulink computer program.

II. DESIGN STEPS

The design procedure of the cross-flow turbine involves the following steps:

1. Preparing the site data

This involves the calculations and measuring the net head of the hydro-power plant and its water flow rate.

a. Calculation of the net head (H_n):

$$H_n = H_g - H_{tl} \quad (m) \tag{1}$$

Where H_g = the gross head which was the vertical distance between water surface level at the intake and at the turbine. This distance can be measured by modern electronic digital levels.

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H_{tl} = total head losses due to the open channel, trash rack, intake, penstock and gate or value. These losses were approximately equal to 6% of gross head.

b. Calculation of the water flow rate (Q):

The water flow rate can be calculated by measuring river or stream flow velocity (V_r) and river cross-sectional area (A_r), then:

$$Q = V_r * A_r \qquad (m^3.s^{-1}) \tag{2}$$

2. Calculation of turbine power (P_t)

The electrical power of the turbine in *Watt* can be calculated as

$$P_t = \rho * g * \eta_t * H_n * Q \qquad (Watt) \tag{3}$$

3. Calculation of turbine efficiency (η_t)

The maximum turbine efficiency can be calculated as [2]:

$$\eta = \frac{1}{2} * C^2 * (1+\psi) * cos^2(\alpha) \tag{4}$$

From equation (4) above, its clear that the attack angle (α) should be kept as small as possible for maximum turbine efficiency. The manufacturing of this type of turbine has shown that arc angle of (16˚) can be obtained without much inconvenience [2].

4. Calculation of the turbine speed (N):

The correlation between specific speed (N_s) and net head is given for the cross-flow turbine as [9]:

$$N_s = {513.25}/{H_n}^{0.505} \tag{5}$$

Also the specific speed interms of turbine power in *Kw*, turbine speed in (*r.p.m*) and net head in (*m*) is given as [9]:

$$N_s = {N * \sqrt{P_t}}/{H_n}^{5/4} \tag{6}$$

From equations (5) and (6) above, the turbine speed can be calculated as:

$$N = {513.25 * H_n^{0.745}}/{\sqrt{P_t}} \qquad (r.p.m) \tag{7}$$

5. Calculation of runner outer diameter (D_o)

At maximum efficiency, the tangential velocity of the runner outer periphery is given as [2]:

$$V_{tr} = \frac{1}{2} * C * \sqrt{2 * g * H_n} * \cos(\alpha) \tag{8}$$

Also

$$V_{tr} = w * \frac{D_o}{2} = \frac{2\pi N D_o}{120} \tag{9}$$

From equations (8) and (9) the runner outer diameter can be calculated as:

$$D_o = 40 * {\sqrt{H_n}}/{N} \qquad (m) \tag{10}$$

6. Calculation of blade spacing (t_b):

The thickness of jet entrance (t_e) measured at right angles to the tangential velocity of runner is given as [2]:

$$t_e = K * D_o \qquad (m) \tag{11}$$

Where K = constant = 0.087

The tangential spacing (t_b) is given as [2]:

$$t_b = {t_e}/{\sin(\beta_1)} = {K * D_o}/{\sin(\beta_1)} \tag{12}$$

Where β_1 = blade inlet angle = 30° when α = 16°. Then

$$t_b = 0.174 * D_o \tag{13}$$

7. Calculation of the radial rim width (a):

It is the difference between the outer radius (r_o) and inner radius (r_i) of the turbine runner, and it is also equal to the blade spacing and can be given as:

$$a = 0.174 * D_o \qquad (m) \tag{14}$$

8. Calculation of the runner blade number (n)

The number of the runner blades can be determined as [2]:

$$n = {\pi * D_o}/{t_b} \tag{15}$$

9. Calculation of the water jet thickness (t_j)

It is also defined as nozzle width and can be calculated as [2]:

$$t_j = {A_j}/{L} = \frac{Q/V_j}{L} = {Q}/{(C * \sqrt{2 * g * H_n} * L)} = {0.233 * Q}/{(L * \sqrt{H_n})} \tag{16}$$

Where A_j = jet area (m^2).

10. Calculation of runner length (L):

The runner length in (m) can be calculated as:

From reference [2]:

$$L * D_o = {210 * Q}/{\sqrt{H_n}} \tag{17}$$

By transforming the British units of equation (17) above into metric units, it can be obtained as:

$$L * D_o = {0.81 * Q}/{\sqrt{H_n}} \tag{18}$$

Substitute equation (10) into (18) to obtain:

$$L = {Q * N}/{(50 * H_n)} \qquad (m) \tag{19}$$

Substitute equation (19) into (16) to obtain:

$$t_j = {11.7 * \sqrt{H_n}}/{N} \tag{20}$$

Also substitute equation (10) into (20) to obtain the jet thickness at maximum efficiency as:

$$t_j = 0.29 * D_o \qquad (m) \tag{21}$$

11. Calculation the distance between water jet and the center of runner shaft (y_1) [2]:

$$y_1 = 0.116 * D_o \tag{22}$$

12. Calculation the distance between water jet and the inner periphery of runner (y_2) [2]

$$y_2 = 0.05 * D_o \tag{23}$$

13. Calculation inner diameter of the runner (D_i) [2]:

$$D_i = D_o - 2 * a \tag{24}$$

14. Calculation of the radius blade curvature (r_c) [2]:

$$r_c = 0.163 * D_o \tag{25}$$

15. Calculation of the blade inlet and exit angles ($\beta_1$and β_2)[2]:

The blade inlet angles can be calculated as [2]:

$$\tan(\beta_1) = 2 * \tan(\alpha) \tag{26}$$

The blade exit angle β_2 = 90° for perfect radial flow, but it must be equal to (β_1) at maximum efficiency.

The Matlab Simulink flow-chart was given in figure (2). The results of the design parameters of the turbine at maximum efficiency with variable site head were given in table **(1)**, while table **(2)** gives the same parameters with variable water flow rate. From these results, the turbine maximum efficiency was constant at 88% with different values of head and flow rate.

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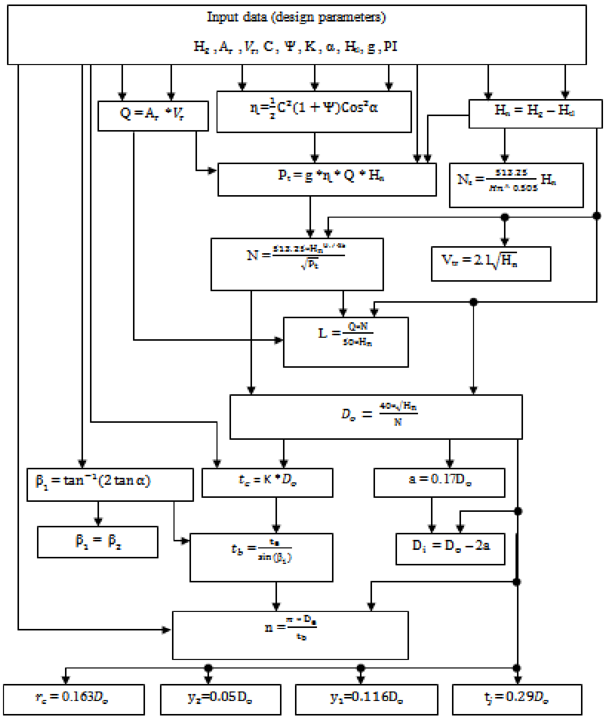

Figure (2) Matlab Simulink flow-chart for design of cross-flow turbine at maximum efficiency

Table **(1)** design results for the parameters of cross-flow turbine at constant flow rate (*$Q = 1\ m^3.s^{-1}$*)

H_g (m)	P_t (Kw)	N (r.p.m)	η %	N_s	L (m)	D_o (m)	D_i (m)	t_b (m)	t_j (m)	y_1 (m)	y_2 (m)	r_c (m)
1	8	172	88	530	3.70	0.225	0.146	0.039	0.065	0.026	0.0110	0.037
2	16	204	88	373	2.17	0.270	0.180	0.047	0.078	0.031	0.0130	0.043
3	24	226	88	304	1.60	0.300	0.190	0.052	0.086	0.034	0.0150	0.048
4	32	242	88	263	1.30	0.320	0.210	0.056	0.093	0.037	0.0160	0.052
5	40	255	88	235	1.10	0.340	0.220	0.060	0.100	0.040	0.0170	0.055
6	48	267	88	214	0.95	0.350	0.230	0.062	0.103	0.041	0.0180	0.058
7	56	277	88	198	0.84	0.370	0.240	0.064	0.107	0.043	0.0185	0.060
8	64	287	88	185	0.76	0.380	0.250	0.066	0.110	0.044	0.0190	0.062
9	73	295	88	175	0.70	0.390	0.260	0.069	0.114	0.045	0.0195	0.064
10	81	303	88	165	0.64	0.400	0.265	0.070	0.117	0.047	0.0200	0.066
11	89	310	88	158	0.60	0.410	0.270	0.072	0.120	0.048	0.0250	0.068

Table **(2)** design results for the parameters of cross-flow turbine at constant head (*$H_g = 10\ m$*)

Q ($m^3.s^{-1}$)	P_t (Kw)	N (r.p.m)	η %	N_s	L (m)	D_o (m)	D_i (m)	t_b (m)	t_j (m)	y_1 (m)	y_2 (m)	r_c (m)
0.1	8	957	88	165	0.20	0.13	0.080	0.0220	0.037	0.015	0.006	0.020
0.2	16	677	88	165	0.30	0.18	0.110	0.0316	0.052	0.021	0.009	0.030
0.3	24	553	88	165	0.35	0.22	0.144	0.0380	0.064	0.025	0.011	0.036
0.4	32	479	88	165	0.40	0.25	0.170	0.0440	0.070	0.029	0.013	0.041
0.5	40	428	88	165	0.45	0.28	0.186	0.0500	0.083	0.033	0.014	0.046
0.6	48	391	88	165	0.50	0.31	0.200	0.0540	0.090	0.036	0.015	0.051
0.7	56	362	88	165	0.54	0.33	0.220	0.0600	0.098	0.039	0.017	0.055
0.8	65	338	88	165	0.57	0.36	0.240	0.0630	0.100	0.042	0.018	0.060
0.9	73	319	88	165	0.61	0.38	0.250	0.0670	0.111	0.044	0.019	0.062
1.0	81	303	88	165	0.64	0.40	0.260	0.0700	0.117	0.047	0.020	0.066
1.1	89	289	88	165	0.68	0.42	0.280	0.0740	0.123	0.049	0.021	0.070
1.2	97	277	88	165	0.70	0.44	0.290	0.0770	0.128	0.051	0.022	0.072
1.3	105	266	88	165	0.73	0.46	0.300	0.0800	0.133	0.053	0.023	0.075
1.4	113	256	88	165	0.76	0.48	0.310	0.083	0.139	0.055	0.024	0.078
1.5	121	247	88	165	0.79	0.49	0.320	0.0870	0.143	0.057	0.025	0.080

III. CONCLUSIONS

The cross-flow turbine is suitable for installing small hydro-electric power plants in case of low head and flow rate. A complete design of such turbines has been presented in this paper. The maximum efficiency was found to be 88% constant for different values of head and water flow rate. The complete design parameters such as runner diameter, runner length, water jet thickness, blade spacing, radius of blade curvature, turbine power, turbine speed and number of blades were determined at maximum turbine efficiency.

IV. NOMENCLATURE

a	Radial rim width (m)
A_r	River cross-sectional area (m^2)
C	Nozzle roughness coefficient (0.98)
D_o	Outer runner diameter (m)
D_i	Inner runner diameter (m)
g	Gravity acceleration constant ($m.s^{-2}$)
H_g	Gross head of the plant site (m)
H_n	Net head of the plant site (m)
H_{tl}	Total head losses (m)
L	Runner length (m)
N	Runner speed (r.p.m)
N_s	Specific speed in metric units
n	Number of blades
P_t	Turbine power (Kw)
Q	Water flow rate ($m.s^{-3}$)
r_c	Radius of blade curvature (m)
r_i	Inner radius of runner (m)
r_o	Outer radius of runner (m)
t_b	Tangential blade spacing (m)
t_e	Thickness of jet entrance (m)
t_j	Water jet thickness (nozzle width) (m)
V_j	Jet velocity before entering ($m.s^{-1}$)
V_r	River or stream water velocity ($m.s^{-1}$)
V_{tr}	Tangential runner velocity ($m.s^{-1}$)
w	Runner angular velocity ($radian.s^{-1}$)
y_1	Distance between water jet and shaft center (m)
y_2	Distance between water jet and inner periphery of runner (m)
Greek symbols	
α	Attack angle (deg.)
$β_1$	Blade inlet angle (deg.)
$β_2$	Blade exit angle (deg.)
η	Turbine efficiency (%)
ρ	Specific water density ($Kg.m^{-3}$)
ψ	Blade roughness coefficient (0.98)

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