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Design of Speed Control System for Pelton Turbine

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Abstract- In hydropower plants, the water turbines are the heart of electricity generation. In this paper, the turbine used for hydropower plant is the Pelton turbine which is one of the impulse turbines. The design data are taken from Wattwon hydropower in Pyin Oo Lwin, Myanmar. This paper is to design the Pelton turbine, its regulating mechanism and speed control system that can develop a power output of 225 kW. The head of water is 213.36m (700 ft) and the speed of the turbine is 1000 rpm. Since it is required to control the quantity of water flowing, the nozzle and the deflector are the main parts of regulating mechanism. The designed nozzle has a jet velocity of 63.73 m/s, jet diameter of 0.052m and nozzle outlet diameter of 0.064m. The other dimensions of the nozzle and the deflector are also calculated. As hydraulic turbines are usually coupled to AC generators which run at a constant speed, it is essential that the speed of the turbine should also remain constant, irrespective of variation in load. This work is done by a device called the governor. In this paper, the specifications of the governor are calculated.

Index Terms- flow rate, head, velocity, Specific Speed, Pelton Turbine

I. INTRODUCTION

Hydraulic turbines extract energy from the flowing water and convert it to mechanical energy to drive electric generator. In Pelton turbine, nozzle and deflector are the main parts for regulating the flow of quantity of water. The nozzle is a circular guide mechanism, which guides the water to flow at a designed direction and also to regulate the flow of water.

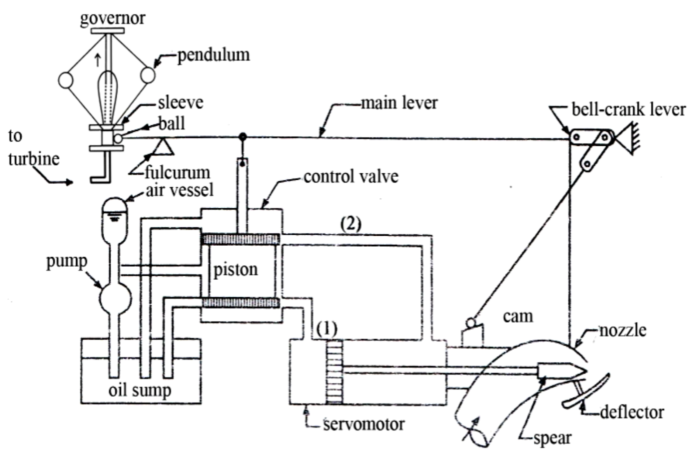

Figure 1. Speed Control System for the Pelton Turbine [1]

II. DESIGN CALCULATION OF SPEED CONTROL SYSTEM FOR THE PELTON TURBINE

A. Design Calculation of the Pelton Turbine

The required design data are selected from Wattwon Hydroelectric Power Station of Pyin Oo Lwin in Myanmar. In this hydroelectric power station, the Pelton turbine is designed for

Power,	P = 225 kW
Turbine speed,	N = 1000 rpm
Head,	H = 700 ft = 213.36 m
Efficiency,	η_0 = 80 % (Assuming)

(i) Determination of the required Volume Flow Rate or Discharge

$$Q = \frac{P}{\eta_0 \rho g H} = 0.134\ m^3/s$$

(ii) Calculation of the Velocity of the Jet, $V = C_v\sqrt{2gH}$

Where, C_v is the coefficient of velocity for the nozzle and its value is ranging from 0.97 to 0.99.

Choose $C_v = 0.985$ (as mean)

$V = 63.73$ m/s

(iii) Calculation of the Diameter of the Jet, $d = \left[\dfrac{4Q}{\pi C_V(\sqrt{2gH})}\right]^{1/2} = 0.542\left(\dfrac{Q}{\sqrt{H}}\right)^{1/2} = 0.052\text{m}$

(iv)Calculation of the Peripheral Velocity of the Runner , $u = \phi(\sqrt{2gH})$

Where, ϕ is speed ratio and in practice the values of ϕ range from 0.43 to 0.47.

Choose $\phi = 0.46$, $u = 29.76$ m/s

(v) Calculation of Mean Diameter or Pitch Circle Diameter of the Pelton Wheel, $D = \dfrac{60\,u}{\pi N} = 0.568\text{m}$

(vi) Calculation of the Jet Ratio, $m = \dfrac{D}{d_0} = \dfrac{0.568}{0.052} = 11$

For the maximum efficiency, the jet ratio should be from 11 to 14.So, the jet ratio, m = 11

(vii) Calculation of Bucket Dimensions

$B = (4 \text{ to } 5)d_0$;

$C = (0.81 \text{ to } 1.05)d_0$;

$M = (1.1 \text{ to } 1.25)d_0$;

Again $\beta = 5^\circ$ to 8°

$L = (2.4 \text{ to } 3.2)d_0$;

$l = (1.2 \text{ to } 1.9)d_0$;

Angle $\Phi = 10^\circ$ to 20°

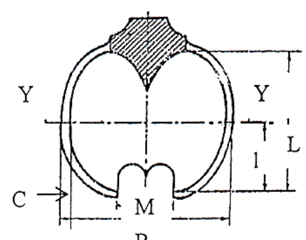

Figure 2.Typical Dimensions of the Pelton Wheel Bucket

Main dimensions of the bucket are;

B =	$4.5\ d_0$	$= 4.5\times 0.052$	= 0.234 m
C =	$0.93\ d_0$	$= 0.93\times0.052$	= 0.048 m
M =	$1.175d_0$	$= 1.175\times0.052$	= 0.061 m
L =	$2.8d_0$	$= 2.8 \times 0.052$	= 0.146 m
I =	$1.55d_0$	$= 1.55\times0.052$	= 0.081 m

(viii) Calculation of the Number of Buckets

$Z = \dfrac{D}{2d_0} + 15 = 20.5$,For balancing of the runner, Z = 21.

B. Calculation of Specific Speed of the Pelton Turbine

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{1000\times\sqrt{225}}{213.36^{5/4}} = 18.4$$

According to Table 1, the specific speed of the Pelton turbine with one nozzle must be between 4 and 35. Hence, the specific speed of the turbine 18.4 is suitable.

Table 1. - Selection of Turbine Based on Specific Speed [13]

No	Specific speed	Type of Turbine
1.	4 to 35	Pelton wheel with 1 nozzle
2.	17 to 50	Pelton wheel with 2 nozzles
3.	24 to 70	Pelton wheel with 4 nozzles
4.	80 to 120	Francis turbine, low-speed
5.	120 to 220	Francis turbine, normal
6.	220 to 350	Francis turbine, high-speed
7.	350 to 430	Francis turbine, express
8.	300 to 1000	Propeller and Kaplan turbines

C. Design Calculation of Regulating Mechanism (Nozzle and Deflector)

(i) Calculation of the Nozzle Outlet Diameter

From Equation 3.5 , the required nozzle outlet diameter is

$$d_1 = \sqrt{\frac{Q\sin\alpha}{2.66\,\mu C_v\sqrt{H}}}$$

where μ = the efflux coefficient (0.8 and 0.88)

Choose μ = 0.84 as mean

Assume α = 80 °

$$d_1 = \left(\frac{0.134\sin 80}{2.66\times 0.84\times 0.985\times\sqrt{213.36}}\right)^{1/2} = 0.064 \text{ m}$$

Checking the nozzle outlet diameter

The nozzle outlet diameter ,

$d_1 = (1.2\sim1.25)\, d_o$

The maximum outlet diameter , $d_{max} = 1.25\, d_o = 0.065$ m

The minimum outlet diameter , $d_{min} = 1.2\, d_o = 0.0624$ m

The above-calculated nozzle outlet diameter is between the maximum and minimum range.

(ii) Calculation of Nozzle Dimensions

All types of nozzle dimensions depend upon the nozzle outlet diameter. Fig. (3) indicates the labels of nozzle dimensions. The detailed dimensions of nozzle are shown in Table 2.

The calculated nozzle dimensions are :

C	=	0.63	×	0.064	=	0.040 m
s	=	1.35	×	0.064	=	0.086 m
x	=	0.503	×	0.064	=	0.032 m
d	=	0.63	×	0.064	=	0.040 m
I	=	3.17	×	0.064	=	0.203 m
r	=	0.705	×	0.064	=	0.045 m
R	=	2.2	×	0.064	=	0.141 m
h	=	0.6	×	0.064	=	0.038 m
e	=	0.05	×	0.064	=	0.003 m
f	=	1.13	×	0.064	=	0.0

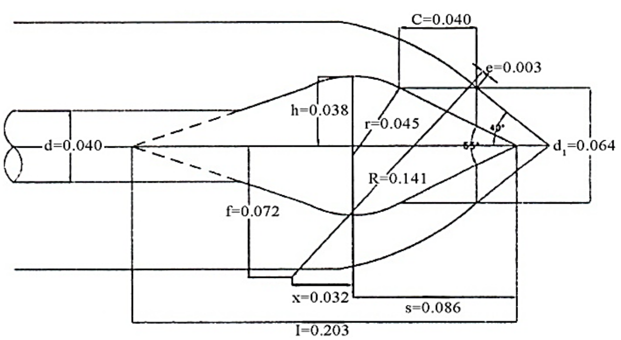

Figure 3. Calculated Dimensions for a Typical Nozzle

Table 2. Nozzle Dimensions [14]

Item	Values
C	0.63 d_1
s	1.35 d_1
x	0.503 d_1
d	0.63 d_1
I	3.17 d_1
r	0.705 d_1
R	2.2 d_1
h	0.6 d_1
c	0.05 d_1
f	1.13 d_1

(iii) Calculation of Deflector Dimensions

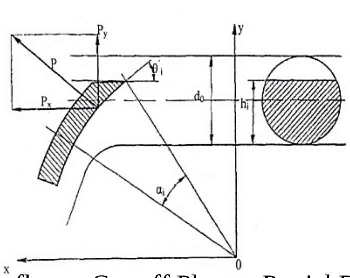

Figure 4. Deflector Cut-off Plate at Partial Deflection for Design Calculation

The most commonly used practical value of θ_i is 30º.

$$P_x = \frac{r}{g} QV - \frac{r}{g} QV \cos \theta_i = \rho QV (l - \cos \theta_i) = 1000 \times 0.134 \times 63.73 (1 - \cos 30^o) = 1144.1 \text{ N}$$

The force acting on the deflector in y-direction determined by $P_y = \frac{r}{g} QV \sin \theta_i = \rho QV \sin \theta_i = 4269.9$ N

The resultant force acting on the deflector described by $P = \sqrt{P_x^2 + P_y^2} =$ 4420 N

The height of the deflected part calculated by $h_i = \frac{d_0}{2} + \frac{d_0}{2} \sin \theta_i = \frac{0.052}{2} + \frac{0.052}{2} \sin 30^o = 0.039$ m

The other dimensions of the deflector are:

$R_1 = 2.32\, d_1 = 3.32 \times 0.064 = 0.148$ m
$L = 1.86\, d_1 = 1.86 \times 0.064 = 0.119$ m
$t = 0.23\, d_1 = 0.23 \times 0.064 = 0.015$ m

D. Design Calculation for Servomotor

Capacity of the servomotor = P × Volume

$$\text{Volume} = \frac{\pi}{4} D^2 L$$

The Stoke length of the needle is $a = \frac{d_1 - 0.5 d_1}{2} \frac{1}{\sin\alpha} = 0.016$ m

Spear stroke must be greater than 0.16 m. Assume that the stroke is 0.03 m.

The force acting on the needle is $F = \frac{\pi}{4}(d_1^2 - d^2)\rho g H = \frac{\pi}{4}(0.064^2 - 0.04^2) \times 1000 \times 9.81 \times 213.36 = 4103$ N

Volume of packing $= \pi r^2 h = \pi \times d^2 \times I = \pi \times 0.040^2 \times 0.203 = 1.02 \times 10^{-3}\ m^3$

Volume of spear $= \left[\frac{1}{3}\pi r^2 h\right]_1 + \left[\frac{1}{3}\pi r^2 h\right]_2 = \left[\frac{1}{3}\pi h^2 \times s\right]_1 + \left[\frac{1}{3}\pi h^2 (I - s)\right]_2 = 3.07 \times 10^{-4}\ m^3$

Total Volume $= 1.02 \times 10^{-3} + 3.07 \times 10^{-4} = 1.327 \times 10^{-3}\ m^3$

Packing Friction force = Friction Coefficient × Total Weight

$= C_f \times \rho V g = 0.3 \times 7870 \times 1.327 \times 10^{-3} \times 9.81 = 30.70$ N

Force applied to control linkage is F= 4103 + 30.70 = 4133.70 N

Servomotor's Capacity=0.03 × 4133.70 = 124 Nm

Servomotor's Capacity = P × Volume

$$\text{Volume} = \frac{\pi}{4} \times 0.15^2 \times 0.03 = 5.301 \times 10^{-4}\ m^3$$

$$P = \frac{\text{Servomotor's Capacity}}{\text{Volume}} = \frac{124}{5.301 \times 10^{-4}} = 234\ kN/m^2$$

E. Calculation of Synchronous Speed Range for the Generator and Speed Ratio $N_g = \frac{120f}{p}$

Assuming p = 4 poles

For minimum synchronous speed for the generator,

Assuming frequency, f = 50Hz ,

$$N_{mini} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

For mean synchronous speed for the generator, Assuming frequency, f = 55Hz ,$N_{mean} = \frac{120 \times 55}{4}$ =1650 rpm

For maximum synchronous speed for the generator,

Assuming frequency, f = 60Hz ,

$$N_{maxi} = \frac{120 \times 60}{4} = 1800 \text{ rpm}$$

$$\text{Speed Ratio} = \frac{\text{Mean Synchronous Speed for Generator}}{\text{Turbine Speed}} = \frac{1650}{1000} = 1.65$$

F. Calculation of the Governor Speed Range

$$\text{Minimum governor speed, } N_1 = \frac{N_{mini}}{1.65} = \frac{1500}{1.65} = 909 \text{ rpm}$$

$$\text{Mean governor speed, } N_2 = \frac{N_{mean}}{1.65} = \frac{1650}{1.65} = 1000 \text{ rpm}$$

$$\text{Maximum governor speed, } N_3 = \frac{N_{maxi}}{1.65} = \frac{1800}{1.65} = 1091 \text{ rpm}$$

G. Calculation of Governor Specifications

Assume that
the length of upper arm = 15 cm
the length of lower arm = 15 cm
the distance between the lower arm and the sleeve from the axis = 2.5 cm
the weight of the governor ball,w = 50 N
the weight of the sleeve = 400 N
the force required to open the control valve = 100 N
W = 400 + 100
= 500 N

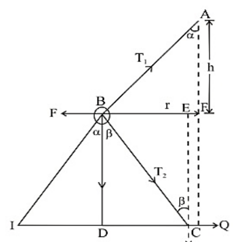

Figure 5. One-half of the Porter Governor for Design Calculation

(i).Calculation of Governor Specifications at Mean Governor Speed

Mean Governor speed, N_{mean} = 1000 rpm

Assume $\alpha_1 = 45^o$
AB = 15 cm
BC = 15 cm
EF = 2.5 cm

$h_1 = AF = AB \cos \alpha_1 = 10.61$ cm

$r_1 = BF = AB \sin \alpha_1 = 10.61$ cm

$$\beta_1 = \sin^{-1}\left(\frac{BE}{BC}\right) = 32.73^o$$

$$k_1 = \frac{\tan \beta_1}{\tan \alpha_1} = \frac{\tan 32.73^o}{\tan 45^o} = 0.64$$

$$F_1 = \left[\frac{W}{2}(k+1)+w\right]\tan\alpha_1 = \left[\frac{500}{2}(0.64+1)+50\right]\times\tan 45^o = 460\ N$$

(ii). Calculation of Governor Specifications at Minimum Governor Speed

Minimum Governor speed, N_{mini} = 909 rpm

Assume $\alpha_2 = 30^o$

$h_2 = AF = AB\cos\alpha_2 = 12.99$ cm

$r_2 = BF = AB\sin\alpha_2 = 7.5$ cm

$$\beta_2 = \sin^{-1}\left(\frac{BE}{BC}\right) = 19.5^o$$

$$k_2 = \frac{\tan\beta_2}{\tan\alpha_2} = 0.61$$

$$F_2 = \left[\frac{W}{2}(k+1)+w\right]\tan\alpha = 261.25\ N$$

(iii). Calculation of Governor Specifications at Maximum Governor Speed

Maximum Governor speed, N_{maxi} = 1091 rpm

Assume $\alpha_3 = 60^o$

$h_3 = AF = AB\cos\alpha_3 = 7.5$ cm

$r_3 = BF = AB\sin\alpha_3 = 12.99$ cm

$$\beta_3 = \sin^{-1}\left(\frac{BE}{BC}\right) = 44.37^o$$

$$k_3 = \frac{\tan\beta_3}{\tan\alpha_3} = 0.56$$

$$F_3 = \left[\frac{W}{2}(k+1)+w\right]\tan\alpha_3 = 762.1\ N$$

Table 3 - Governor Specification Results

N (rpm)	h (cm)	α(degree)	β(degree)	F(N)
N_{mean} = 1000	10.61	45	32.73	460
N_{mini} = 909	12.99	30	19.5	261.25
N_{maxi} = 1091	7.5	60	44.37	762.1

III. CONCLUSION

The Pelton turbine has been designed at the head of 213.36m (700 feet) at the turbine speed of 1000 rpm and the flow rate of water (0.134 m^3/s) to generate 225 kW output power, assuming its overall efficiency of 80%. The required power output of the generator can be obtained from both the maximum speed (1800 rpm) and the minimum speed (1500 rpm). In this paper, the various speeds of governor have been calculated by depending on the speed generator. The designs of the nozzle and the deflector have been calculated as the regulating mechanism of the turbine to get the required flow rate of water. And the governing system designs have been calculated as the speed control system.

APPENDIX

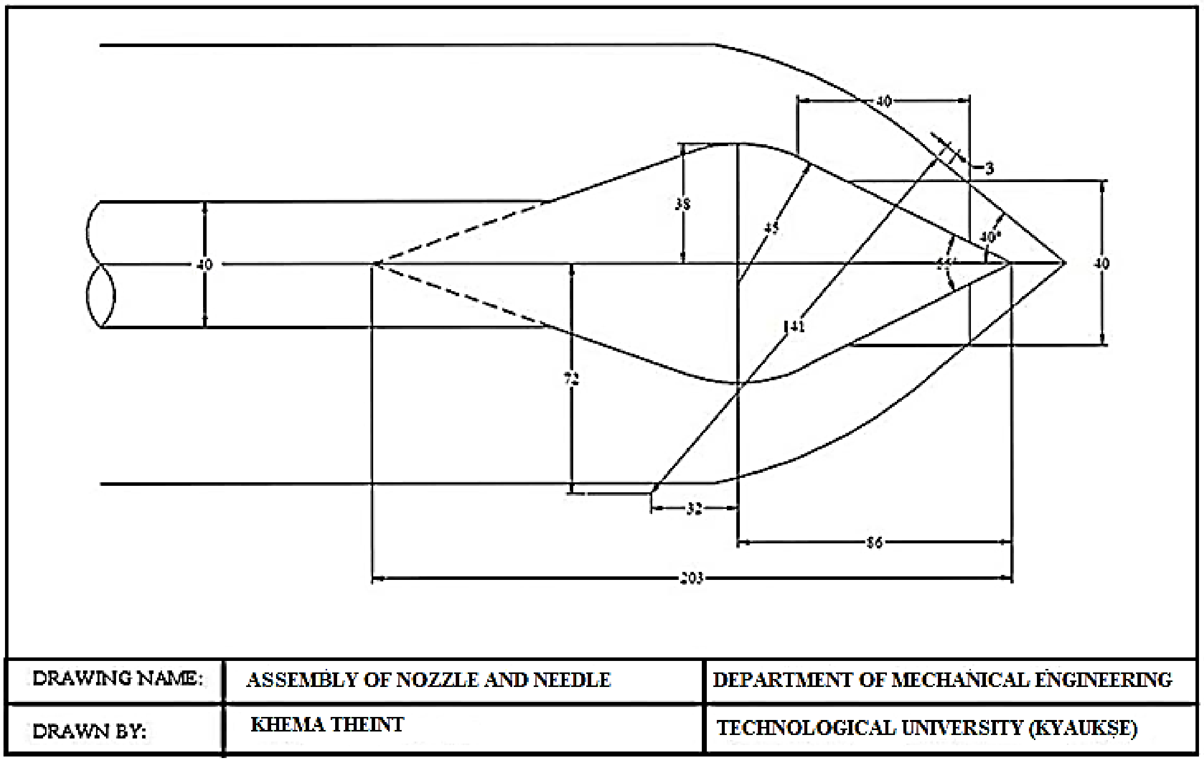

Figure A.1. Assembly of Nozzle and Needle

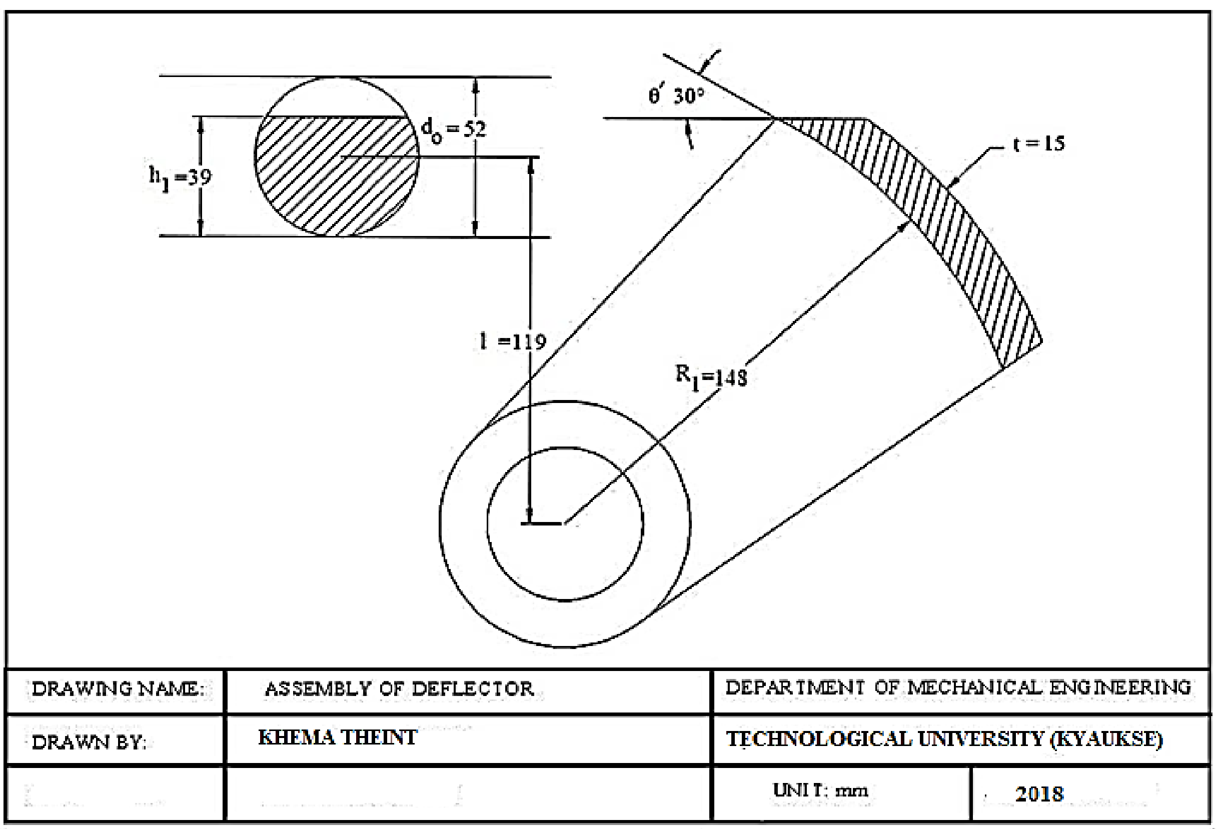

Figure A.2. Assembly of Deflector

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