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Design of 225kW Pelton Turbine

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Abstract: Renewable energy to produce electricity is an essential role all over the world. The electricity generation of hydro power is relatively cheaper than the power generated by other sources. The main goal of this paper is to study the technologies of hydraulic turbines and to design the Pelton turbine that is suitable for high head conditions. In a hydropower plant, the kinetic energy of flowing water is transformed into mechanical energy by use of a turbine. This turbine is designed based on the model turbine by using the similarity law. From the testing result, the rotational speed is 1432rpm and net head is 29.1m. To design Pelton turbine, the required data is based on Wetwin hydropower station in Myanmar. Therefore, the required head is 213 m to generate 225 kW output power. The flow rate of this turbine is 0.16 m^3/s and the pitch circle diameter is 1.4 m. Number of pole for generator is 10poles and the speed of the turbine is 369.4 rpm. The diameter of the jet is 57 mm and jet ratio is 24.53 mm. The number of bucket is 27.The detail drawing of nozzle and bucket are described in this paper.

Keywords: Bucket Design, Jet Diameter, Pelton Turbine.

I. INTRODUCTION

Hydraulic turbine can be defined as a rotary machine, which uses the potential and kinetic energy of water converts it into useful mechanical energy. According to the way of energy transfer, there are two types of hydraulic turbine namely impulse turbine and reaction turbine. In impulse turbine water coming out of the nozzle at the end of the penstock is made to strike a series of buckets fitted on the periphery of the runner. In reaction turbine, water enters all around the periphery of runner and the runner remains full of water every time. The water that leaves from the runner is discharged into the tailrace with a different pressure. Therefore casing is necessary for reaction turbines. Pelton turbine is an impulse turbine. The runner of the Pelton turbine consists of double hemispherical cups fitted on its periphery as shown in Fig.1.

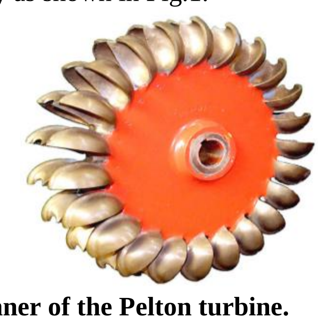

Fig.1.The runner of the Pelton turbine.

The jet strikes these cups (buckets) at the central dividing edge of the front edge. The central dividing edge is also called as splitter. The water jet strikes edge of the splitter symmetrically and equally distributed into the two halves of hemispherical bucket. Theoretically, if the buckets are exactly hemispherical, it will deflect the jet through 180 degree. Then the velocity of the water jet leaving the bucket would be opposite in direction to the velocity of jet entering. Practically, this could not be achieved the jet leaving the bucket strikes the back of succeeding bucket and the overall efficiency would decrease. In practice, the angular deflection of the jet in the bucket is limited to about (165 to 170 degree). The amount of water discharges from the nozzle is regulated by a needle valve provided inside the nozzle as shown in fig.2.

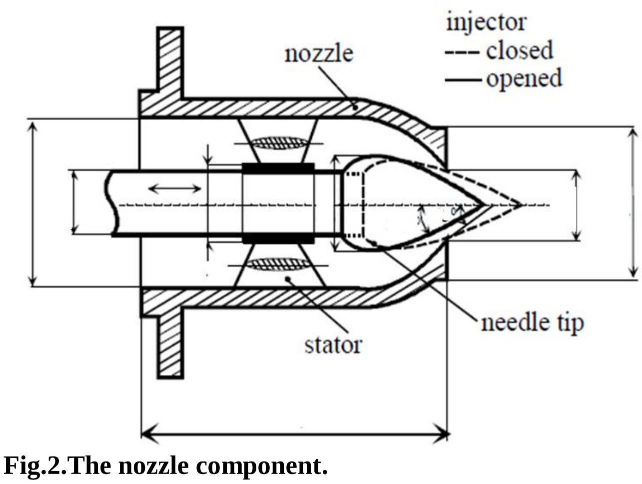

Fig.2.The nozzle component.

II. TYPES OF HYDRAULIC TURBINE

Turbines are used for converting hydraulic energy into electrical energy as shown in Fig.3. Turbine are also classified by their principal ways of operating and can be either impulse or reaction turbines.

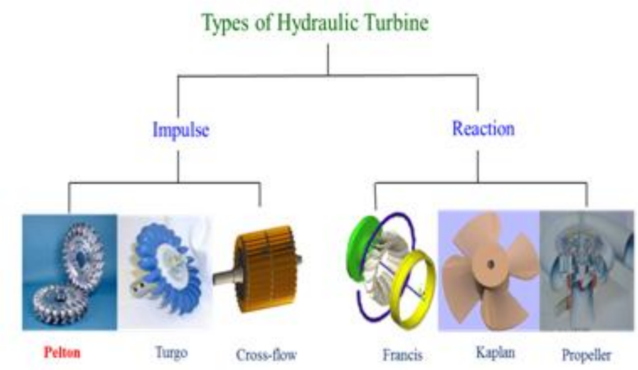

Fig.3. Hydraulic turbine.

The Pelton turbine is an impulse turbine used for high head and low flow rate. The model 12 Pelton turbine is tested in a laboratory which is suited in Mandalay Technological University to obtain performance curve. By using similarity law, Pelton turbine for 225 kW is designed based on testing result of model 12 Pelton turbine. And then, the nozzle and bucket design of Pelton turbine are described. After calculating the design, the turbine assembly and detail drawing are also described.

III. THEORETICAL BACKGROUND

The jet of water issuing from the nozzle strike the bucket at its splitter then split up the jet into two parts. One part of the jet glides over the inside surface of one portion of the bucket and leaves it at its extreme edge. The transfer of work from the jet of water to buckets takes places according to the momentum equation. To estimate the work output and the efficiency of a Pelton turbine, references is made to the inlet and outlet velocity triangles as shown in Fig.4.

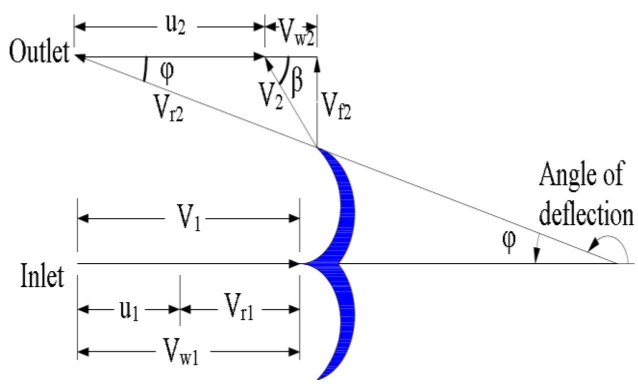

Fig.4.Velocity triangle for Pelton turbine.

where,

- V_1 - absolute velocity of water at inlet,
- V_{r1} - jet velocity relative to bucket at inlet,
- V_{w1} - velocity of whirl at inlet,
- u_1 - tangential velocity of wheel,
- V_2 - absolute velocity of water at outlet,
- V_{r2} - jet velocity relative to bucket at outlet,
- V_{w2} - velocity of whirl at outlet,
- V_{f2} - velocity of flow at outlet,
- ϕ - angle made by the relative velocity with the direction of motion of the vane at outlet,
- β - angle made by the absolute velocity with the direction of motion of the vane at outlet.

Force exerted by the jet of water in the direction of motion is;

$$F = ma = m^{\bullet}dV \quad (1)$$

$$F = \rho a V_1 (V_{w1} + V_{w2}) \quad (2)$$

Now work done by the jet on runner per second can be calculated as;

$$W.D = F \times U \quad (3)$$

$$W.D = \rho a V_1 (V_{w1} + V_{w2}) U \quad (4)$$

The energy supply to the jet at inlet is in the form of kinetic energy and is equal to

$$\frac{1}{2} m V_1^2 \quad (5)$$

Therefore kinetic energy of jet per second is;

$$KE = \frac{1}{2}(\rho a V_1) \times V_1^2 \quad (6)$$

Hydraulic efficiency of the turbine can be calculated as,

$$= \frac{\rho a V_1 (V_{w1} + V_{w2}) u}{\frac{1}{2}(\rho a V_1) V_1^2}$$

$$\eta_h = \frac{2(V_{w1} + V_{w2})U}{V_1^2} \quad (7)$$

From inlet and outlet velocity triangles,

$$U = U_1 = U_2 \quad (8)$$

$$V_{w1} = V_1 = V_{r1} - U_1 \quad (9)$$

$$V_{w2} = V_{r2}\cos\phi - U = K(V_1 - U)\cos\phi - U \quad (10)$$

Substituting the values of V_{w1} and V_{w2} in equation(7), For maximum hydraulic efficiency of a Pelton turbine,

$$\eta_h = \frac{2[(V_1 - U)(1 + K\cos\Phi)]U}{V_1^2} \quad (11)$$

The hydraulic efficiency will be maximum for given value of V_1 when,

$$\frac{d}{dU}(\eta_h) = 0$$

$$\frac{d}{dU}\frac{2[(V_1 - U)(1 + K\cos\Phi)]U}{V_1^2} = 0$$

$$\frac{2(1 + K\cos\Phi)}{V_1^2} \neq 0, \frac{d}{dU}(V_1 U - U^2 = 0)$$

$$V_1 - 2U = 0$$

$$U = \frac{V_1}{2}$$

$$U = 0.5V_1 \quad (12)$$

IV. DESIGN CALCULATION OF 225 KW PELTON TURBINE

There are many hydropower plants using Pelton turbine in Myanmar. They are described in the following table.

Table I: Hydropower Station Using Pelton Turbine In Myanmar

Name	Head (m)	Flow rate (m^3/s)	Power (kW)	Turbine type
Kyeinkayan	164	0.53	630	Pelton
Hopin	191	0.42	630	Pelton
No.1 Watwin	213	0.16	225	Pelton
No.2 Watwin	213	0.16	225	Pelton
Nam Wop	338	0.38	1000	Pelton
Laiva	194	0.46	175	Pelton
Lahal	59	0.11	50	Pelton

Source: From M.E.P.E:

In this paper, the required data is based on Wetwin hydropower station. The design calculation of this turbine is based on model 12 Pelton turbine. Design calculation will be described as follow.

Power, p = 225 kW
Available head, H = 213 m
Acceleration due to gravity, g = 9.81 m/s^2
Coefficient of velocity, C_v = 0.98
Density of water, ρ = 1000 kg/m^3
Flow rate , Q = 0.16 m^3/s

The design calculation of 225 kW Pelton turbine is based on model 12 Pelton turbine.

A. Performance Testing Of Model 12 Pelton Turbine

Model 12 Pelton turbine is tested in a Laboratory which is suited in Mandalay technological University. The resource of required water is carried from the ground tank. The water from the ground tank is pumped to the artificial water way by using the pump. The required jet opening is set by turning the hand wheel in anti-clockwise direction. The speed of the turbine is measured by using a tachometer. In this test, nozzle position of Pelton turbine is placed five positions. There are 1.5, 2/5, 3/5, 4/5 and fully open position. Head is change in every position. The pitch circle diameter of model 12 Pelton turbine is 96 mm and jet diameter is 10 mm. In 1/5 open position.
Head, H = 29.1 m
Turbine speed, N = 2280 rpm
Load = 0.1 kg

$$\text{Flow rate, } Q = \text{lbh/time (for bucket area method)} \quad (13)$$

Water horse power,

$$WHP = \rho g Q H \quad (14)$$

Break power,

$$B.P = \frac{2\pi NT}{60} \quad (15)$$

Efficiency,

$$\eta = \frac{B.P}{WHP} \quad (16)$$

The characteristic curve of Pelton turbine is shown in Fig.5.

Fig.5. Laboratory scale of model 12 Pelton turbine.

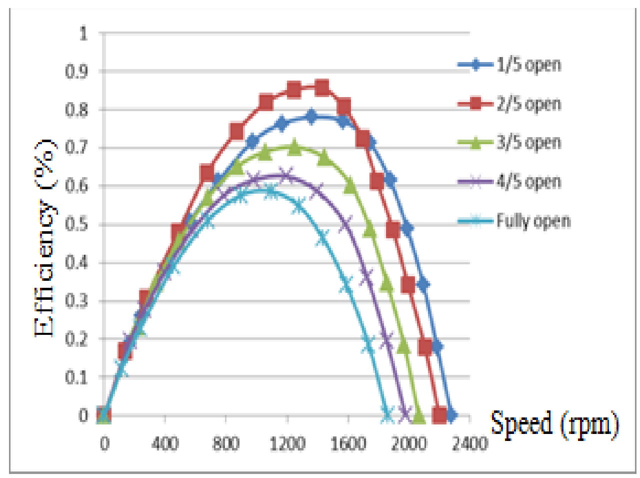

Fig.6. Relationship between speed and efficiency curve.

B. Design Calculation of the Secificspeed

Relationship between speed and efficiency curve are obtained from the experiment results of model 12 Pelton turbine as shown in Fig.6. In this performance curve the maximum efficiency occur 2/5 opening position. The best operating point obtained at the maximum efficiency of the turbine. The best operating output power of model 12 Pelton turbine is 113.16 W. The flow rate is 0.4628×10^{-3} m^3/s and the head is 29.1 m. By using similarity law,

Specific speed,

$$(Ns)_m = \frac{N\sqrt{P}}{(H)^{5/4}} \quad (17)$$

Any turbine, with identical geometric proportions, even if the sizes are different, will have the same specific speed. By using dynamic similarity, the specific speed relationship between model and prototype turbine can be obtained.

C. Calculation of the Turbine Speed

The correlation between specific speed (Ns) and the net head of the Pelton turbine as,

$$N = \frac{N_s H^{5/4}}{\sqrt{P}} \quad (18)$$

The number of poles can be obtained,

$$N = \frac{120f}{P} \quad (19)$$

D. Design Aspects of Pelton turbine

The following points must be considered while designing a Pelton turbine.

The velocity of the jet ,

$$V_1 = C_v \sqrt{2gH} \quad (20)$$

The tangential velocity of the wheel is determined the following factors.

$$U = k_u \sqrt{2gH} \quad (21)$$

Assume, speed ratio, $k_u = 0.46$

The mean diameter or pitch circle diameter of the Pelton turbine is given by

$$U = \omega \times R_r = \frac{\pi DN}{60} \quad (22)$$

So, diameter of runner is,

$$D = \frac{60 \times U}{\pi \times N}$$

Thus the jet diameter of 225 kW double jet Pelton can be calculated from continuity equation;

$$q = AV \quad (23)$$

$$Q = \frac{\pi d_0^{\,2}}{4} \times n \times C_v \sqrt{2gH}$$

$$d_0 = \sqrt{\frac{4Q}{n \ \pi C_v \sqrt{2gH}}}$$

$$d_0 = 0.545 \sqrt{\frac{Q}{n\sqrt{H}}}$$

E. Design Calculation Of Number Of Buckets

Jet ratio,

$$m = \frac{D}{d_o} \quad (24)$$

$$z = \frac{D}{2d_0} + 15 = 0.5m + 15 \quad (25)$$

Curvature of the bucket is as shown in Fig.7.

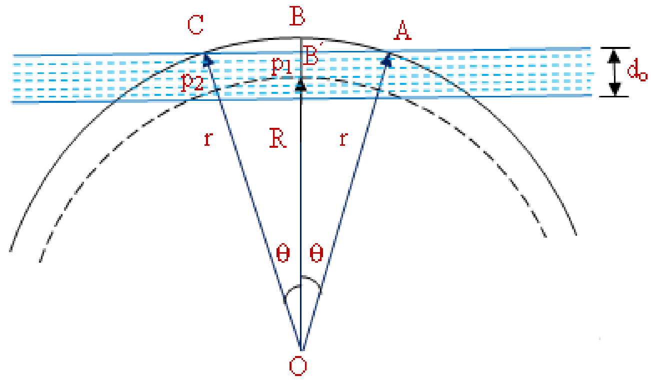

Fig.7.Curvature of the bucket.

The angle subtended by adjacent buckets at the centre of the wheel is calculated as,

$$z = \frac{360}{\theta}$$

$$\theta = \frac{360}{z}$$

In Δ AOB';

$$\cos\theta = \frac{R + 0.5d_0}{r}$$

The bucket pitch,

$$p_1 p_2 = \frac{2\pi R}{z} \quad (26)$$

From inlet and outlet velocity triangle,

Relative velocity of water,

$$V_{r1} = V_1 - u_1$$

$$V_{r2} = KV_{r1}$$

Assume, blade friction coefficient K = 1

Whirl velocity of water,

$$V_{w1} = V_1$$

$$V_{w2} = V_{r2} \cos\phi - u_2$$

Flow velocity of water, V_{f2}

$$\sin\phi = \frac{V_{f2}}{V_{r2}}$$

Absolute velocity of water at outlet, V_2

$$\cos\beta = \frac{V_{w2}}{V_2}$$

Jet force on the runner, F

$$F = \rho a V_1 (V_{w1} + V_{w2}) \quad (27)$$

Work done by the jet on the runner per second, W.D

$$W.D = F \times u \quad (28)$$

F. Bucket Weight

Jet force on the bucket, P_0

$$P_0 = \rho a V_1 \frac{(V_1 - u)^2}{V_1}(1 - \cos\alpha) \quad (29)$$

The centrifugal force,

$$C.F = F\text{-}P_0 \quad (30)$$

$$C.F = \frac{Gu^2}{gR} \quad (31)$$

G. Bucket Design

In routine design the dimension of the bucket are determined according to the diameter of the jet (d_0). The main dimensions of the bucket of a Pelton turbine are express in terms of the jet diameter as shown in Fig.8;

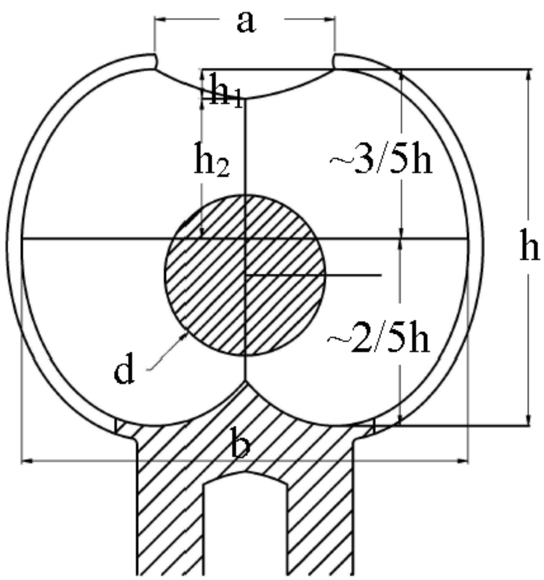

Fig. 8.Bucket dimension of Pelton turbine/

Bucket width, b = 2.5 – 3.2 times jet diameter
Bucket height, h = 2.1 – 2.7 times jet diameter
Bucket depth, t = 0.9 d_0
Width of bucket opening, a = 1.2 d_0
Offset of bucket, k = 0.1- 0.17times jet diameter
Notch width of bucket,h_1= 0.1 – 0.35times jet diameter
Notch to jet centre distance, h_2 = 0.85-1.5 times jet diameter

H. Nozzle Design

The dimensions of the nozzle are determined according to the diameter of the jet (d_0).

Nozzle diameter, d_n = 1.15-1.25 times jet diameter
Blocking space needle to nozzle tip, C = 0.45times jet diameter
Location of needle tip radius, S = 1.35 times jet diameter
Location of nozzle orifice radius, X = 0.503 times jet diameter
Diameter of spear shaft, d = 0.45 times jet diameter
Length of needle tip, I = 3.17 times jet diameter
Curve of needle tip radius, r = 0.705 times jet diameter
Curve of nozzle orifice radius, R = 2.2 times jet diameter
Height of needle tip, h = 0.6 times jet diameter

I. Design Calculation Of Shaft Diameter

The torsional moment acting of the shaft, M_t

$$M_t = \frac{9550 \times P}{N} \quad (32)$$

The transmitted force, F_t

$$F_t = \frac{M_t}{R} \quad (33)$$

Diameter of shaft, d_s

$$d_s = \sqrt[3]{\frac{1.77 \times 10^6 P}{N}} \quad (34)$$

V. RESULT DATA FOR 225KW PELTON TURBINE

Some parameters of Pelton turbine are assumed to design the runner. If the surface of bucket is perpendicular to the jet axis, the maximum force will obtain when the angle of deflection is 180°. In practice, the angle of deflection is taken 165° because the leaving water of bucket can strike behind the earlier bucket. The calculated results in Table II are parameters of nozzle design. Results of 225 kW Pelton turbine is shown in Table III. Comparison of existing and calculated data are shown in Table IV.Fig.9 illustrates the nozzle shape with sectional 3D view and Fig.10 show the 2D assembly of Pelton bucket. And then, the assembly of double jet Pelton turbine is shown in Fig.11.

TABLE II: Results Table for Nozzle Dimensions

Items	Calculated Values (mm)	Existing Values (mm)
Nozzle diameter, d_n	65	63
Optimum distance between nozzle and wheel, O_d	361	360
Blocking space needle to nozzle tip , C	26	25
Location of needle tip radius, S	77	75
Location of nozzle orifice radius, x	29	*
Diameter of spear shaft, Φ	25	25
Length of needle tip, I	180	*
Curve of needle tip radius, r	40	*
Curve of nozzle orifice radius, R	125	*
Height of needle tip, h	34	30

TABLE III: Results table for 225kW Pelton turbine

No.	Type	Unit	Calculated data
1.	Speed of turbine, N	rpm	396.4
2.	Specific speed, N_s	*	7.3
3.	Velocity of jet, V_1	m/sec	63.676
4.	Tangential velocity, u	m/sec	29.737
5.	Pitch circle diameter, D	m	1.4
6.	Jet diameter, d_0	m	0.057
7.	Jet ratio, m	*	24.53
8.	Number of buckets, z	*	27
9.	Bucket pitch, p_1p_2	mm	162
10.	Outlet relative velocity, V_{r2}	m/sec	33.939
11.	Outlet whirl velocity, V_{w2}	m/sec	3.046
12.	Outlet flow velocity, V_{f2}	m/sec	8.784
13.	Outlet absolute velocity, V_2	m/sec	8.9
14.	Outlet angle at exist, β	°	70°
15.	Jet force on the runner, F	N	10690.08
16.	Work done, W.D	kW	317.89
17.	Centrifugal force, C.F	N	7845.914
18.	Shaft Power, S.P	kW	275
19.	Bucket width, b	mm	162
20.	Bucket height, h	mm	137
21.	Bucket depth, t	mm	52
22.	Width of bucket opening, a	mm	68
23.	Offset of bucket, k	mm	189
24.	Notch width of bucket, h_1	mm	20
25.	Notch width to jet centre distance, h_2	mm	67
26.	Diameter of shaft, d_s	mm	105

TABLE IV: Comparison of Existing and Calculated Data

No.	Type	Unit	Calculated data	Existing data
1.	Flow rate, Q	m^3/s	0.16	0.16
3.	Bucket width, b	mm	162	160
4.	Bucket height, h	mm	137	135
5.	Bucket depth, t	mm	52	50
6.	Width of bucket opening, a	mm	68	65
7.	Offset of bucket, k	mm	189	190
8.	Notch width of bucket, h_1	mm	20	25
9.	Notch width to jet centre distance, h_2	mm	67	65
10.	Number of bucket, Z	*	27	27
11.	Diameter of shaft, d_s	mm	80	85

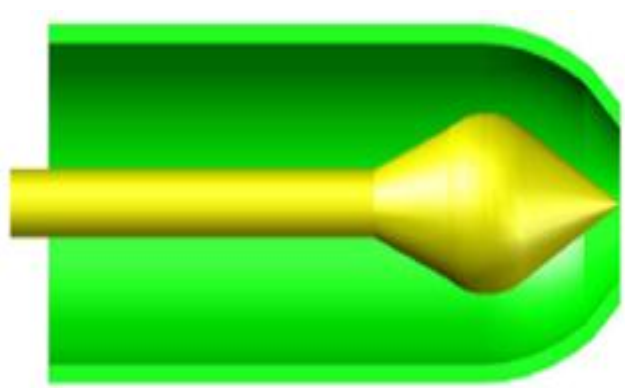

Fig.9.Sectional 3D view of Pelton nozzle.

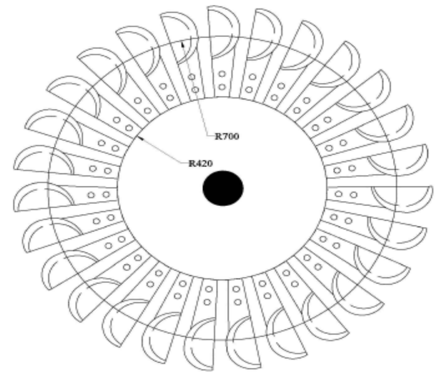

Fig.10.2D assembly of Pelton bucket.

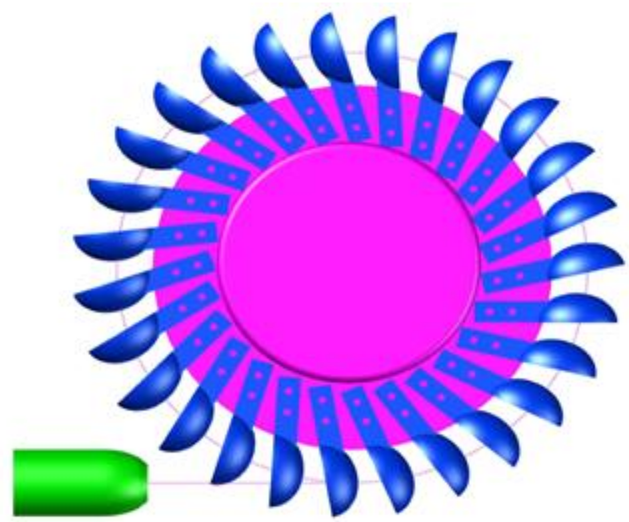

Fig.11.Asseembly of Pelton turbine.

VI. DISCUSSIONS AND CONCLUSIONS

A hydroelectric power plant uses a renewable source of energy that does not pollute the environment. In hydropower plant, turbine is the most important part to generate electricity. As water sources vary, water turbines have been designed to suit different locations. The design used depends on the head and quantity of water available at that site. The output power of turbine depends on the head and flow rate. The different types of turbines are briefly discussed in this research. Among these turbines, Pelton turbine is designed. Pelton turbine is impulse turbine with single or multiple jets, each jet issuing through a nozzle with a needle valve to control the flow. They are used for medium or high heads. In this research, double jet is used for this design. The nozzle and buckets are the most important part of Pelton turbine. Design of the optimum, complex shape of the buckets to obtain maximum power output is a very difficult matter. For the hydraulic design, the number of buckets is an essential parameter.

In this research, Model 12 Pelton turbine is tested to use similarity law. Five nozzle positions are placed with the various speeds during the test. Relationship between speed and efficiency curve are obtained from the experiment results of model turbine. At 1/5 open position of nozzle, the efficiency decreases immediately because the area of nozzle is too small. At small the cross-sectional area, it does not affect the power but large amount of area affects power and efficiency. At 3/5, 4/5 and fully open position of nozzle, the efficiency decrease because of the cross-sectional area of nozzle is inversely proportional to the pressure. In this performance curve, the maximum efficiency occurs 2/5 opening nozzle position. The best operating point is obtained at the maximum efficiency of turbine. The efficiency of Pelton turbine is maximum when the tangential velocity is half the velocity of jet of water at inlet. In this point, the efficiency of model turbine is 85%, speed ratio is 0.43 and the flow rate is 0.4628×10^{-3} m^3 /sec at the turbine's speed of 1432rpm.

The required data is based on Wetwin hydropower station in Myanmar. Therefore, the required head is 213m to generate 225kW output power. The flow rate of this turbine is $0.16m^3$/sec and the pitch circle diameter is 1.4m. Number of poles of generator is 14 poles and the speed of turbine is 369.4rpm. The diameter of jet is 57mm and jet ratio is 24.53. The number of bucket is 27. The diameter of jet is important in the bucket design. These bucket dimensions must be between maximum and minimum value with respect to jet diameter. The bucket width is 162mm, the bucket height is 137mm, bucket depth is 52mm, notch width of bucket is 20mm and width of bucket opening is 68mm. For every Pelton turbine design, width of the bucket opening must be larger than the diameter of jet in order to avoid the usable power wasting. The nozzle should be kept close to the turbine wheel in which to minimize the losses due to windage. The detail drawing of nozzle and bucket of that turbine is described in this paper.

VII. ACKNOWLEDGMENT

The author would like to thank his supervisor, head and all of his teachers from Department of Mechanical engineering, Mandalay Technological University who gave good suggestions, guidance and supervision for supporting this research.

VIII. NOMENCLATURE

A = Area of nozzle, m^2
a = Jet area
C_v = Velocity coefficient, (0.98 to 0.99)
d_0 = diameter of nozzle, m
C.F = Centrifugal force
D = Diameter of runner, m
C_v = Velocity coefficient, (0.98 to 0.99)
f = Frequency
F = Force exerted by the jet of water
g = Acceleration due to gravity, m/s^2
G = Weight of bucket
k_u = Speed ratio
m = Mass of water
m_j = Jet ratio
n_j = Number of jet
N = Rotational speed, rpm
N_s = Specific speed
P_0 = Jet force on the bucket, N
P = Power, kW
Q = Water flow rate, m^3/s
R = Radius of pitch circle, mm
r = Radius of the outer circle, mm
U = Absolute velocity of wheel, m/s
V = Jet velocity, m/s
W.D = work done, kW
Z = Number of buckets

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