Design Calculation of Pelton Turbine for 220 kW

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Abstract- In Myanmar, there are various natural resources such as water, air, wind and solar. Among of them, water resource is the most abundant as there are many rivers and streams with rich electrical energy. Moreover, the cost of hydro-electric power is relatively cheaper compared with other resources. In hydraulic turbine is one of the most important parts to generate electricity. This paper intends to design the runner and nozzle with needle for Pelton turbine that will generate 220 kW output power from head of 213 m and flow rate of 0.135 m^3/s. For these head and capacity of turbine, rotational speed is 1000 rpm, specific speed is 18.4, pitch circle diameter is 0.56 m, jet diameter is 0.053 m and nozzle outlet diameter is 0.064 m. The number of bucket based on jet ratio, 11 is 21. Detail design of runner, nozzle with needle of that turbine is described in this paper.

Index Terms- Pelton turbine, output power, head, bucket, nozzle

I. INTRODUCTION

IN Myanmar, the main sources of energy for generating electricity are hydropower because of her hilly regions with rivers and water-falls. Hydropower is an eco-friendly clean power generation method that has been widely used throughout the world. In Myanmar, where 75% of the populations live in rural area, has a low level of village access to electricity. Myanmar has abundant hydro energy sources and the Geography, Topography of the country is favorable for hydropower supply system. A hydropower generation system for remote area in Myanmar is mainly classified into run-of-river type and reservoir type.

Several inherent advantages have been mentioned for hydro-power generation including,

(1) Simplicity of its technology, which is available and only requires adaptation to specific conditions in order to reduce costs.

(2) Viability as a means of providing electricity, particularly in rural and isolated areas, without any need for imported fuel supply.

(3) Contribution to the promotion of industrial, socio-economic and cultural development of the rural environment.

(4) The long lifetime of the structure and machinery, requirements in the locality.

(5) Adaptability of scale designed for specific user requirements in the locality.

(6) Compatibility with the use of water for other purposes such as irrigation and drinking water supply, thereby improving investment.

(7) A supplement to the regional or national grid.

According to above mentioned particulars, there are three types of hydropower plants, such as micro, mini and small hydropower. The power that can be obtained from a stream of water depends on the amount of water flowing and the height from which it flows down the pipe to the turbine. The main types of turbine used in hydropower plants are impulse and reaction turbines.

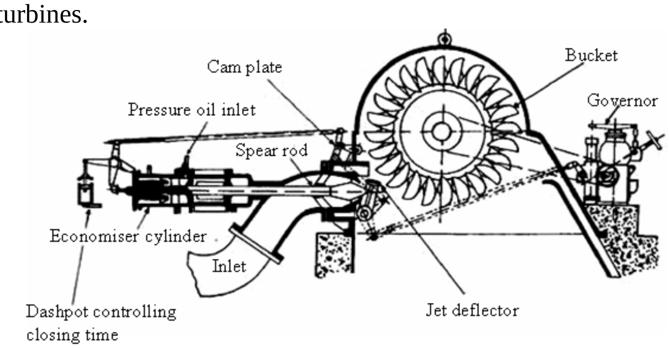

Fig. 1 Main Components of Pelton Turbine [1]

The Pelton turbine is an impulse turbine used for high head and low flow. These turbines are simple to manufacture, are relatively cheap and have good efficiency and reliability. Water is taken to the turbine from the reservoir through penstocks. The penstock is a large pipe fitted with a nozzle at the end. Water comes out of the nozzle in the form of a jet. The whole of hydraulic energy is converted into kinetic energy at the nozzle. The pressure all over the wheel is constant and equal to atmosphere, so that energy transfer occurs due to purely impulse action. A Pelton turbine has one or more nozzles discharging jets of water which strike a series of buckets mounted on the periphery of a circular disc. The runner consists of a circular disc with a number of buckets evenly spaced round its periphery. The buckets have a shape of a double semi-ellipsoidal cup. Each bucket is divided into two-symmetrical parts by a sharp edged ridge known as a splitter. The jet of water impinges on the splitter, which divides the jet into two equal portions, each of which after flowing round the smooth inner surface of the bucket leaves it at its outer edge.

II. REQUIRED PARAMETERS FOR PELTON TURBINE DESIGN

Myanmar Electric Power Enterprise has identified an exploitable potential of 39,624MW on 267 sites. Existing hydropower plants constitute 360 MW (30% of the generating capacity), and hence only 1% of the exploitable potential has been developed.

In this paper, design specification are as follow.

Expected output power, P = 220 kW
Effective head, H = 213 m

Overall efficiency, η = 78%
Density of water, ρ = 1000 kg/m^3
Acceleration due to gravity, g = 9.81 m/s^2

220kW turbine is intended to mini-hydropower plant and flow rate of this turbine, Q will be obtained by power equation.

$$P = \eta \rho g Q H \tag{1}$$

By Equation (1), the required flow rate for expected output power is 0.135 m^3/s.

A. Specification of Suitable Turbine Type

The suitable type of turbine can be classified depending on net head and flow rate as shown in Fig. 2. Since head and flow rate ranges, 213 m and 0.135 m^3/s are within the range of Pelton turbine type, Pelton turbine type is selected.

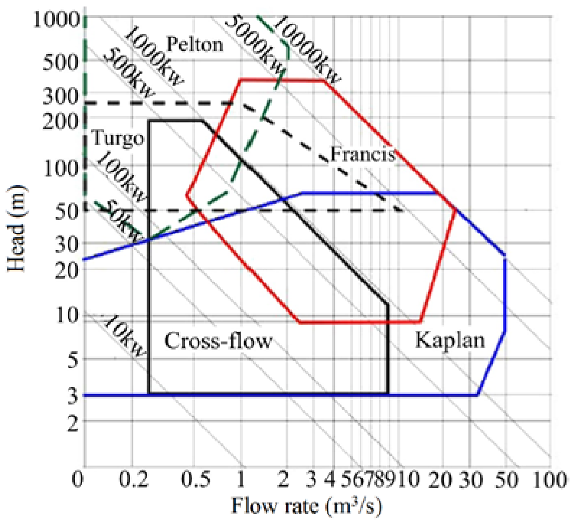

Fig. 2 Turbine Type Based on Head and Flow Rate [2]

B. Determination of Specific Speed and Rotational Speed

Specific speed plays in an important role for selecting the type of turbine. And also the performance of turbine can be predicted by knowing the specific speed of the turbine. The specific speed of a turbine is the speed of geometrically similar turbine that would develop one horse power (metric) when working under a head of one meter. Once the specific speed is known, the fundamental dimensions of the turbine can be easily estimated. The value of specific speed for Pelton turbines with single jet fluctuate between 8.5 and 30. The selected turbine type is single jet Pelton turbine type and the value of specific speed for this type can be calculated by using the following equation.

$$N_S = 85.49 / H^{0.245} \tag{2}$$

The rotational speed of a turbine is directly linked to its specific speed, flow and net head. The rotational speed of turbine is directly or through a speed increaser to the turbine, should reach the synchronous speed. The rotational speed of turbine is

$$N = \frac{N_s H^{5/4}}{\sqrt{P}} \tag{3}$$

In the hydro scheme, standard generator is installed when it is possible, either directly coupling or through a speed increaser should reach the synchronous speed. The number of pole for synchronous speed generator is always even number and it is expressed by

$$P_o = \frac{120 f}{N} \tag{4}$$

Where, f is frequency (50 Hz) and the calculated number of pole is 6. Based on number of pole as shown in Table I, the generator synchronization speed is 1000 rpm and for direct coupling system, rotational speed of turbine is also 1000 rpm.

Table I. Generator Synchronization Speed [2]

Number of poles (P_o)	Frequency 50Hz	Frequency 60Hz	Number of poles (P_o)	Frequency 50Hz	Frequency 60Hz
2	3000	3600	16	375	450
4	1500	1800	18	333	400
6	1000	1200	20	300	360
8	750	900	22	272	327
10	600	720	24	250	300
12	500	600	26	231	277
14	428	540	28	214	257

C. Prediction of Shaft Diameter

The turbine shaft will transmit the rotary motion of the runner to the generator. In most cases, the shaft has a circular cross-section and it subject to either pure torsion or a combination of torsion and bending. The diameter of a shaft to transmit a given power can be determined from the following formula.

$$d_s = \sqrt[3]{\frac{1.77 \times 10^6 \times P}{N}} \tag{5}$$

Since it is difficult to predict the bending moment at this time, the estimated shaft diameter will be slightly increased.

D. Inlet and Outlet Velocities of Pleton Wheel

In Pelton turbine, water flows over the runner and leaves the runner at its outlet point. To estimate the required parameters for bucket design, nozzle design, work output and efficiency of Pelton turbine, reference is made to the inlet and outlet velocities of pelton wheel. Inlet and outlet velocities triangles of Pelton wheel are shown in Fig. 3.

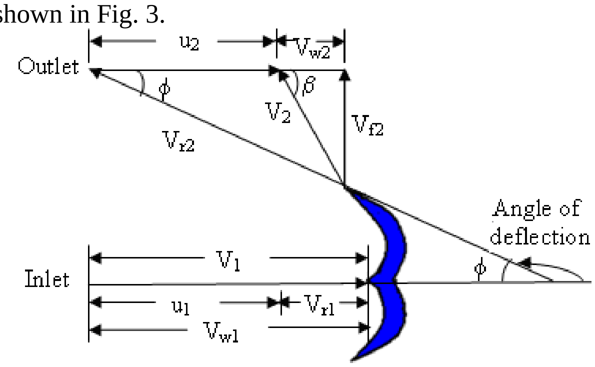

Fig. 3 Inlet and Outlet Velocity Triangles of Pelton Wheel [1]

Where,

V_1 = absolute velocity of water at inlet (m/s)
V_{r1} = jet velocity relative to bucket at inlet (m/s)
V_{w1} = velocity of whirl at inlet (m/s)
u_1 = tangential velocity of wheel at inlet (m/s)
V_2 = absolute velocity of water at outlet (m/s)
V_{r2} = jet velocity relative to bucket at outlet (m/s)
V_{w2} = velocity of whirl at outlet (m/s)
u_2 = tangential velocity of wheel at outlet (m/s)
V_{f2} = velocity of flow at outlet (m/s)

β = angle made by the absolute velocity with the direction of vane motion

ø = angle made by the relative velocity with the direction of vane motion

The jet emerging from the nozzle hits the splitter symmetrically and is equally distributed into the two halves of hemispherical bucket. The inlet angle of the jet is therefore between 1° to 3°, but it is always assumed to be zero in all calculations. Then the relative velocity of the jet leaving the bucket would be opposite in direction to the relative velocity of the entering jet. This cannot be achieved in practice since the jet leaving the bucket would then strike the back of the succeeding bucket to cause splashing and interference so that overall turbine efficiency would fall to low values. In practice, the angular deflection of the jet in the bucket is limited to about 165° and the angle, ø is adopted 15° to keep the jet clear of the succeeding bucket.

The ideal velocity of just usually is known as spouting velocity, $V_1 = \sqrt{2gH}$. However, the actual velocity of the jet is slightly less, due to friction loss in the nozzle. Thus,

$$V_1 = C_v\sqrt{2gH} \tag{6}$$

The coefficient of velocity, C_v account for friction losses in the nozzle and has a value ranging from 0.97 to 0.99 [4]. In this paper, the mean value 0.985 is used for it.

The tangential velocities at inlet and outlet of runner will be same at the mean pitch. Therefore, $u = u_1 = u_2$. For the maximum efficiency, the tangential velocity of wheel at pitch circle, u is equal to $0.5V_1$ [4]. However, in actual practice the maximum efficiency occur when the value of u is about $0.46V_1$. In this relation, this coefficient of V_1 is also known as speed ratio, k_u.

From inlet and outlet velocity triangles, relative velocity of water at inlet is

$$V_{r1} = V_1 - u_1 \tag{7}$$

The relative velocity of water at outlet, V_{r2} is KV_{r1} and blade friction co-efficient, K is slightly less than unity. Ideally when bucket surfaces are perfectly smooth and energy losses due to impact at splitter in neglected, K=1.

III. Design of Bucket

A. Pitch Circle Diameter and Jet Diameter

Mean diameter or pitch circle diameter of the Pelton turbine refers to the diameter of the wheel measured upon the centers of the buckets.

$$u = \frac{\pi DN}{60} \tag{8}$$

Where, D = pitch circle diameter of pelton wheel (m)

And then, the diameter of jet is an important parameter in the design of Pelton wheel and it is determined at the maximum charge by using continuity equation.

$$Q = aV_1 = \frac{\pi d_0^2}{4} \times Z_0 \times C_V\sqrt{2gH}$$

Thus,

$$d_0 = 0.545\sqrt{\frac{Q}{Z_0\sqrt{H}}} \tag{9}$$

Where, d_0 = jet diameter (mm) and
Z_0 = number of nozzle

B. Jet Ratio and Number of Bucket

The ratio of pitch circle diameter of Pelton wheel to the jet diameter is known as jet ratio represented by m and it is a size parameter for the turbine. For maximum hydraulic efficiency, the jet ratio lies between 11 and 15 [4]. A smaller value of m results in either too close a spacing of the buckets or too few buckets for the whole jet to be used. A larger value of m results in a more bulky installation.

$$m = \frac{D}{d_0} \tag{10}$$

The number of buckets for a Pelton wheel should be such that the jet is always completely intercepted by the buckets so that volumetric efficiency of the turbine very closes to unity. The number of buckets is usually more than 15. Certain empirical formulae have been developed for determining the number of buckets. One such formula which is widely used has been given by Taygun according to which the number of buckets, Z is approximately given by

$$Z = 0.5m + 15 \tag{11}$$

Table II. Approximate Number of Buckets for a Pelton Turbine [3]

Jet ratio	6	8	10	15	20	25
No: of bucket	17-21	18-22	19-24	22-27	24-30	26-33

C. Dimensions of Bucket Design Curvature

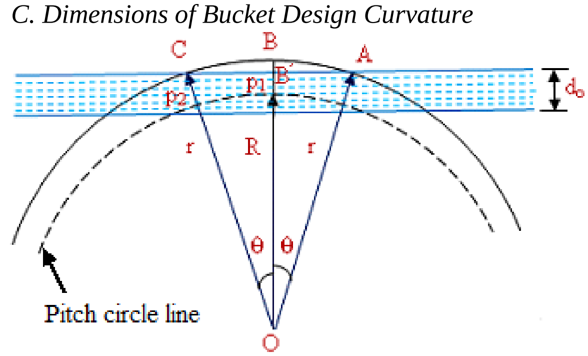

Fig.4 Curvature of Bucket [1]

Where, R = radius of pitch circle
d_0 = diameter of the water jet
p_1p_2 = bucket pitch
r = radius of the outer circle
A, B, C = positions of three adjacent buckets
θ = angle subtended by adjacent buckets at the centre of the wheel

$$Z = \frac{360}{\theta} \tag{12}$$

In ΔAOB′,

$$\cos\theta = \frac{R + 0.5d_0}{r} \tag{13}$$

The bucket pitch on the pitch circle can be obtained by the following equation.

$$p_1 p_2 = \frac{2\pi R}{Z} \tag{14}$$

In a Pelton turbine design, two parameters are important. These are the ratio of the bucket width to the jet diameter and the ratio of the wheel diameter to the jet diameter. If the bucket width is too small in relation to jet diameter, the fluid is not smoothly deflected by the buckets and in consequence, much energy is dissipated in turbulence and the efficiency drops considerably. On the other hand, if the buckets are unduly large, friction on the surfaces is unnecessarily high. The optimum value of the ratio of bucket to the jet diameter has found to be 2.8 and 4. Some of the main dimensions for the Pelton wheel bucket are shown in Table III.

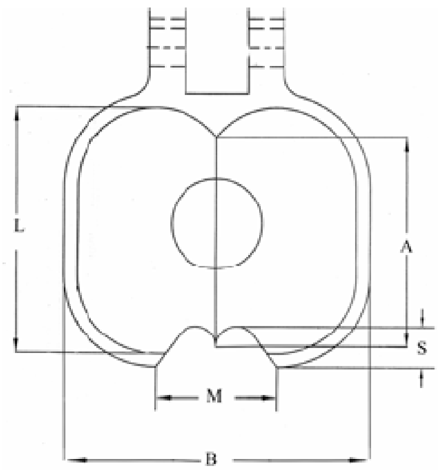

Fig. 5 Bucket Dimensions for Pelton Turbine [6]

Table III. Dimensions of Bucket Based on Jet Diameter [6]

Item	Minimum Value	Maximum Value
Bucket length, L	2.28 d_o	3.3 d_o
Bucket width, B	2.8 d_o	4 d_o
Notch depth, S	0.44 d_o	0.625 d_o
Notch width, M	1.12 d_o	1.6 d_o
Bucket depth, E	0.8 d_o	1.2 d_o
Bucket height, A	1.75 d_o	2.5 d_o

In this paper, the parameters for curvature of bucket design base on Fig. 6. In this referenced design, the bucket sections are divided into five parts and the notch width of bucket is 0.36 times of bucket width, M = 0.36 B. The notch width must be larger than the diameter of jet and it can also be obtained by using the following equation.

$$M = 1.1 d_0 + 5 \tag{15}$$

If the other parameters for design curvature are also taken depending on the bucket width,

Bucket length, L = 0.82B
Notch depth, S = 0.16B
Bucket depth, E = 0.36 B and
Bucket height, A = 0.64B

These parameters must be between maximum and minimum value respect to jet diameter in Table III.

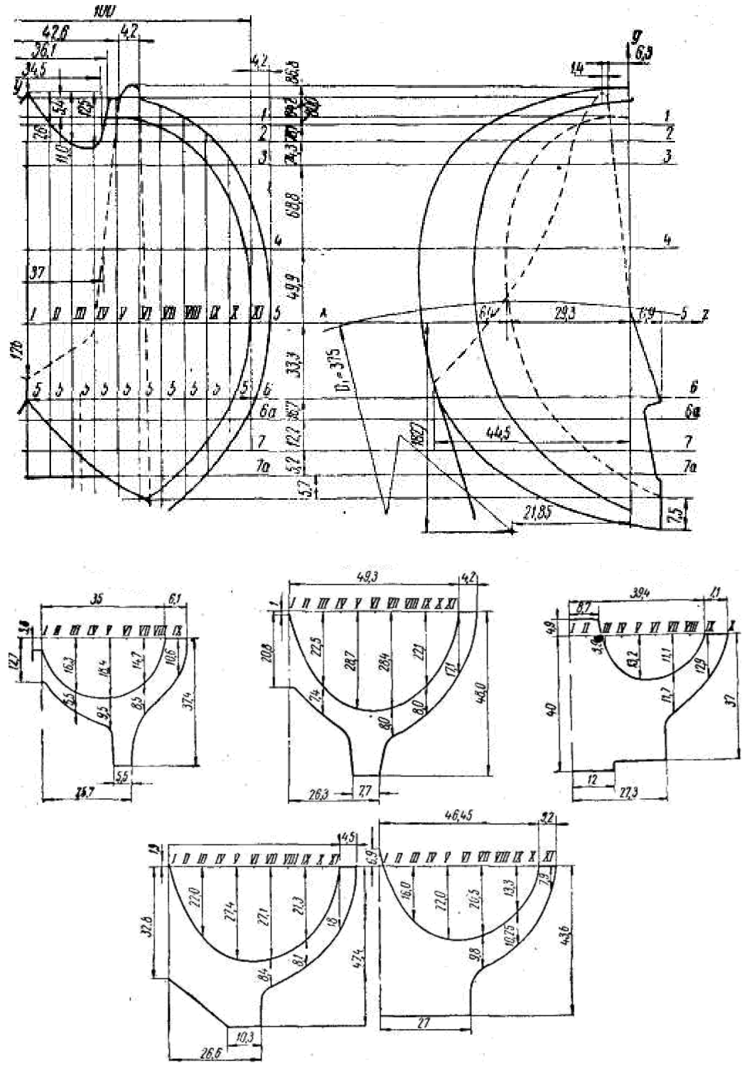

Fig. 6 Referenced Design of a Structure Stream To-461 Bucket Turbine [3]

IV. Design of Nozzle

The nozzle tip and needle should be so proportional as to give a constantly decreasing stream area from a point within the nozzle to a point in the jet beyond the tip of the needle, so that the water may be continuously accelerated. This must be so for every position of the needle. The curve of the must therefore change from convex to concave and the point of inflection must be a diameter greater than that of the nozzle tip, otherwise the water will tend to leave the needle at the smaller openings with a resulting tendency to corrosion.

The diameter of the orifice of the nozzle tip must be greater than the diameter of the jet, due to the contraction of the latter and also to the space taken up by the needle tip, which is never entirely withdrawn. In this paper, three different types of nozzle design that are more useful for Pleton turbine are described and main dimensions of all types base on nozzle outlet diameter.

A. Nozzle Outlet Diameter

The magnitude of the outlet cross section of the nozzle must be established in such a way that at the given head, *H* it allows the given flow-rate, *Q* to pass. The outlet cross section of the nozzle at the position of the needle according to Fig. 7 is given by the relation.

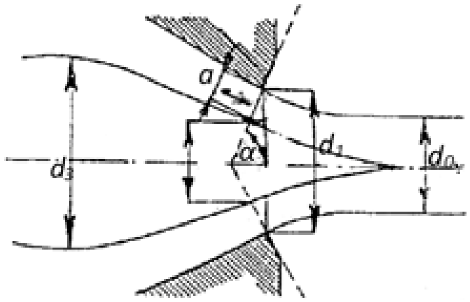

Fig. 7 Cross Section of Nozzle at the Position of the Needle [6]

From Fig. 7, required equation for nozzle outlet diameter, d_1 is

$$d_1 = \sqrt{\frac{Q \sin \alpha}{2.66 \mu C_v \sqrt{H}}} \tag{16}$$

The nozzle outlet diameter, d_1 must be within the range (1.2 ~ 1.25)d_0. The efflux coefficient, μ is between 0.8 and 0.88 [6]. Assume, μ = 0.84 and α = 80º.

B. Dimensions of Nozzle and Needle

Nozzle dimension is depending upon the nozzle outlet diameter. The profile of nozzle and needle design

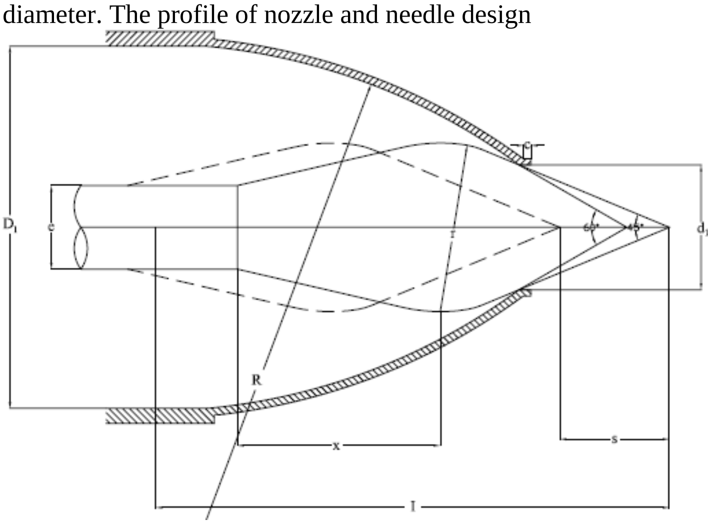

Fig. 8 Profile of Nozzle and Needle [6]

Table IV. Nozzle Dimensions

Item	Values	Results (m)
s	0.88 d_1	0.056
r	1.35 d_1	0.086
x	1.63 d_1	0.104
R	5.02 d_1	0.321
D_1	2.9 d_1	0.186
e	0.67 d_1	0.043
c	0.06d_1	0.004
I	4.12d_1	0.264

V. Results of Designed Turbine

The calculated results in Table V are parameters of runner design for 220 kW output power based on net head, 213 m. Moreover, main dimensions for bucket curvature based on referenced design Fig. 6 are shown in Table VI.

Table V. Required Parameters for Runner Design

No	Description	Symbol	Value
1	Flow rate of water at jet	Q	0.135 m^3/s
2	Specific speed	N_s	18.4
3	Speed of wheel	N	1000 rpm
4	Absolute velocity at inlet	V_1	66.676m/s
5	Tangential velocity at outlet	u	29.29 m/s
6	Pitch diameter of the wheel	D	0.56 m
7	Jet diameter	d_0	0.053 m
8	Nozzle outlet diameter	d_1	0.064 m
9	Jet ratio	m	11
10	Number of buckets	Z	21
11	Angle substandard by adjacent bucket	θ	17.14 deg
12	Relative velocity of water at inlet	V_{r1}	34.39 m/s
13	Relative velocity of water at outlet	V_{r2}	34.386m/s
14	Whirl velocity of water at inlet	V_{w1}	63.676m/s
15	Whirl velocity of water at outlet	V_{w2}	3.924 m/s
16	Velocity of flow at outlet	V_{f2}	8.90 m/s
17	Angle at exit runner	β	66 degree
18	Absolute velocity at outlet	V_2	9.65 m/s
19	shaft diameter	d_S	75 mm

Table VI. Main Dimensions for Bucket Curvature

Item	Minimum Value	Maximum Value	Average Result Value
Bucket length, L	120.8 mm	174.9 mm	144 mm
Bucket width, B	148.4 mm	212 mm	175 mm
Notch depth, S	23.3 mm	33.1 mm	28 mm
Notch width, M	59.4 mm	84.8 mm	63 mm
Bucket depth, E	42.4 mm	63.6 mm	63 mm
Bucket height, A	92.8 mm	132.5 mm	112 mm

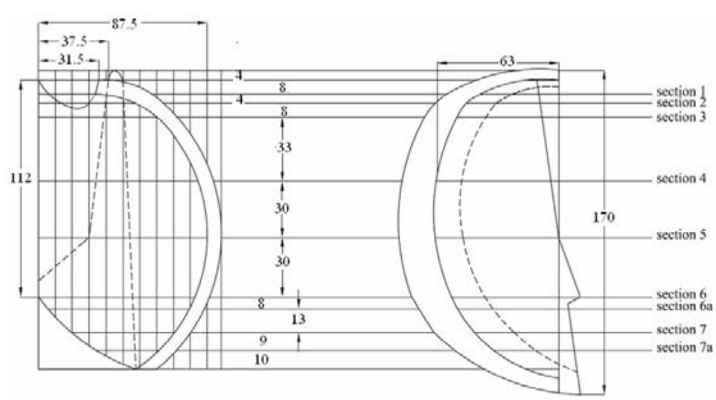

Fig.9 Front View and Side View of Bucket

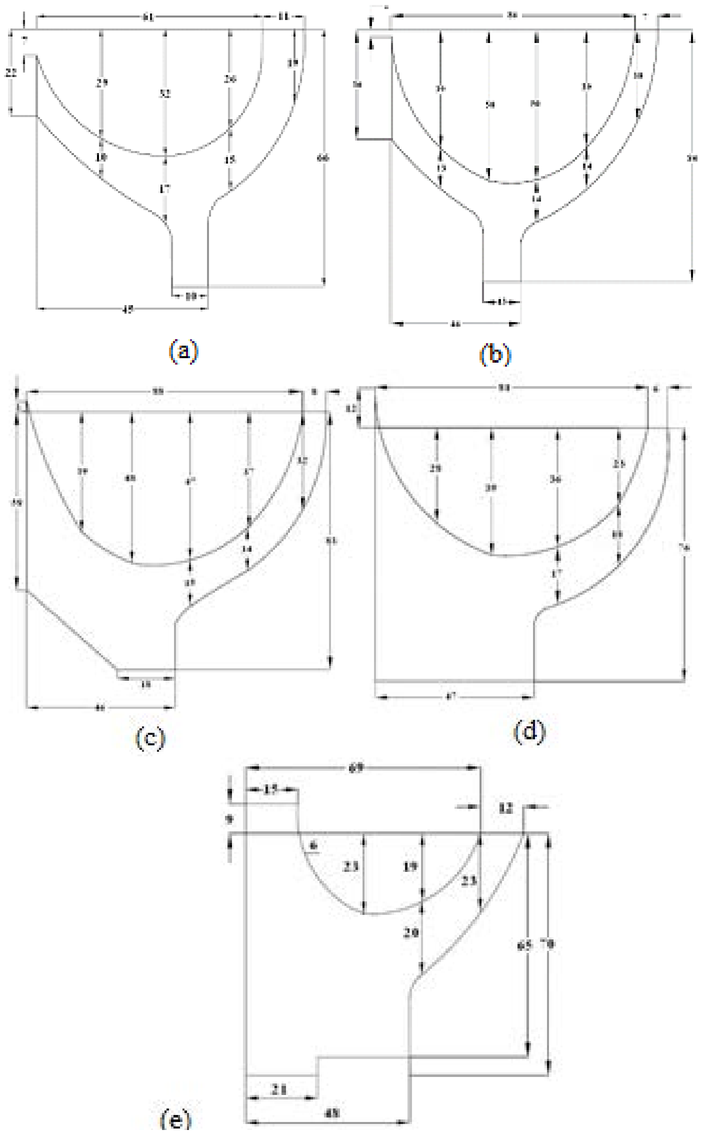

Fig.10 Five Section of Bucket Curvature: (a) Section Two, (b) Section Four, (c) Section Five, (d) Section Six and (e) Section Seven

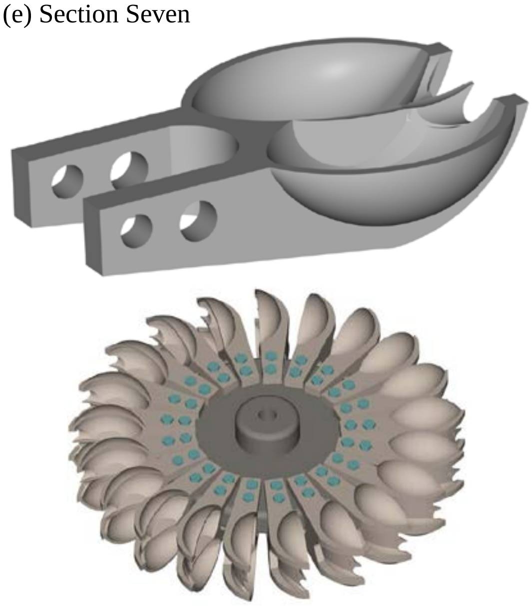

Fig.11 Bucket and Runner for Designed Pelton Turbine

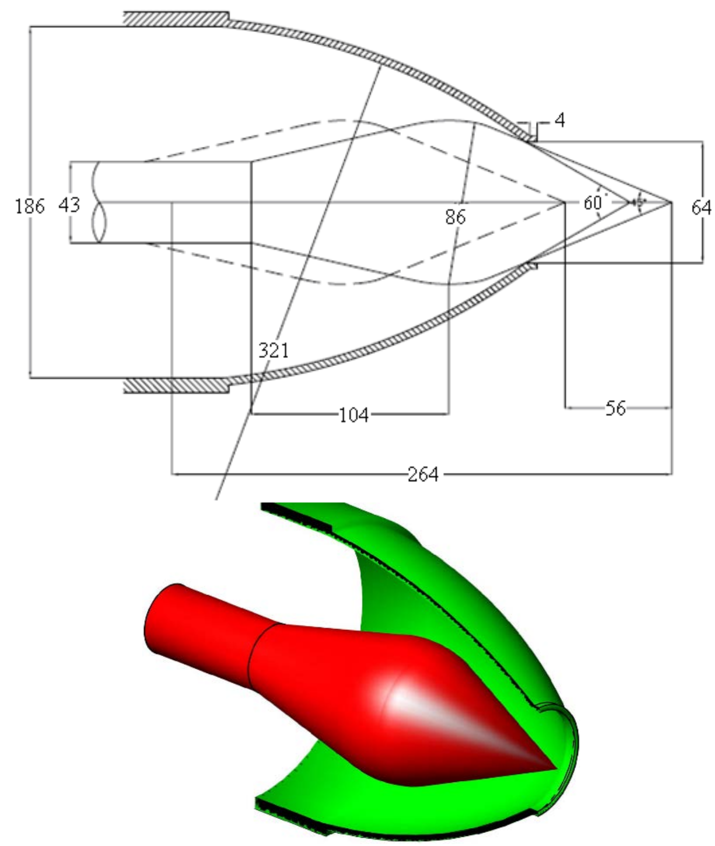

Fig.12 Nozzle with Needle for Designed Pelton Turbine

VI. Conclusion

In hydropower plant, turbine is one of the most important parts to generate electricity. The output power of turbine depends on the head and flow rate. The designed turbine can develop a power of 220 kW on the designed head 213 m and the designed flow rate 0.138 m^3/s. The rotational speed and specific speed of turbine is 1000 rpm and 18.4 respectively. In this paper, detail design of bucket and nozzle with neddle for single jet Pelton turbine is presented. Bucket dimensions must between maximum and minimum value with respect to jet diameter. The jet diameter is 0.053 m. Notch width of the bucket must be larger than the diameter of jet. If the notch width is smaller than the diameter of jet, some of the incoming water would not strike the next bucket. Besides, all of the hydraulic energy cannot be obtained in this condition and many losses can be occurred. It is important that the jet is always completely intercepted by the buckets so that the volumetric efficiency of the turbine very closes to unity. The angle made by the relative velocity with the direction of motion of vane at outlet, is less than 90 degree and the velocity of whirl is negative. In Pelton turbine, nozzle is also one of the main parts because the available fluid energy is converted into kinetic energy by the nozzle. In this study, single jet nozzle is being used because many nozzle turbine interfered by the big bend of channels to bring the collector. In nozzle design, the calculated result of nozzle outlet diameter must be within the range between $1.2d_0$ and $1.25d_0$. The detail dimensions of nozzle and needle shape is mainly depending on the nozzle outlet diameter that is 0.064 m. In this study, detail drawing of runner and nozzle with needle are expressed.

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