

Design of Cross Flow Turbine and Analysis of Runner's Dimensions on Various Head and Flow Rate

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Abstract- There are various natural resources such as water, air, wind and solar in Myanmar. Among 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 hydropower systems, hydraulic turbine is one of the most important parts to generate electricity. This paper represents the runner design of Cross-flow turbine that will generate 100 kW output power from head of 28 m and flow rate of 0.5 m³/s. For these head and capacity, rotational speed is 600 rpm, specific speed is 95.39, runner diameter is 340 mm and runner width is 416 mm. In this paper, detail design drawing of runner are also clearly presented. Moreover, the runner's diameter and breadth are represented with various flow rate range of 0.2 to 1 m³/s and head range of 10 m to 50 m. Thus, it is easy to select the suitable runner's dimensions on the corresponding head and flow rate.

Index Terms- Cross-flow turbine, head, flow rate, output power, blade curvature, runner's dimensions

I. INTRODUCTION

IN Myanmar, hydropower is the main sources of energy for electricity because there are many hilly regions with river and water falls. Myanmar, where 75% of the populations live in rural area has a low level of village access to electricity. It has abundant hydro energy sources and the Geography, Topography of the country is favorable for hydropower supply system. A hydropower classified into run-of-river type and reservoir type. The main advantages of hydropower are: (1) The power is usually available when needed, (2) The amount of energy proportional to the head, (3) No air pollution or radioactive-waste problem, (4) No contribution to global warming and (5) One of the most effective solutions of the production of electricity.

According to above mentioned particulars, there are three types of hydropower plants, such as micro, mini and small hydropower plants. The power depends on the amount of water flowing and the height from which it flows down the pipe to the turbine. There are two types of turbine used in hydropower plant, and these are impulse and reaction types. The Cross-flow turbine is an impulse type and it is used for low and medium head site. Moreover, it is very suitable for micro and mini hydropower generation because of the quite simple to construct and the capability following wide fluctuation of water flow.

II. WORKING PRINCIPLE AND COMPONENTS OF CROSS-FLOW TURBINE

Cross-flow turbine type has a drum shaped runner made of a series of curved blades fixed on two parallel disks. In this turbine, the water velocity is compound of two stages. The jet of water flows firstly from outside to inside of the runner. After crossing the interior of the runner, it flows inside to outside of the runner again.

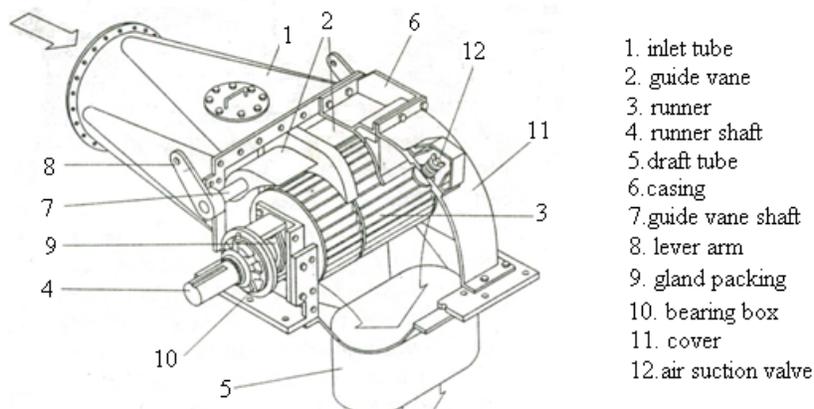


Fig. 1 Main Components of Cross-flow Turbine [1]

Before designing the turbine, the components, operation principle and performance characteristics must be studied. Main components of cross-flow turbine are nozzle, runner, shaft, bearing, casing, draft tube, guide vane and air valve. In this turbine, nozzle is rectangular shape that its width matches the width of runner. Its primary function is to convert the total available head into kinetic energy and simultaneously convey the water to the runner blades at a desired angle. The turbine casing must be well built and sturdy, as it manages forces of the incoming water as well as the outgoing shaft power. Casing shape and dimensions have a significant effect on efficiency. Draft tube is attached below the casing. In order to utilize the draft effect, the tube end is submerged under the tail water level. Its function to recover a major portion of the residual energy left in the water flow coming out of the runner, the head between the turbine and tail water. The shaft is the component of mechanical devices that is used to transmit power from hydraulic power to mechanical power. The runner is one of the most important parts of the turbine. The function of runner is responsible for the conversion of water energy into mechanical energy. Blades are curved and mounted between two rims parallel to the axis of the shaft. Their function is to change the direction of the incoming flow from the nozzle smoothly. The curvature of each surface, front and rear, determines how the water will push its way around until it falls away. All runners should be carefully balances to minimize vibration, a problem that not only affects efficiency but can also cause damage over time. The runner of the cross-flow turbine is made up of two end plates, a shaft and 24 to 30 blades arranged radially around the end plates.

The diameter of runner is an important and basic factor for the design of runner. It can be determined from the speed and water head. From the turbine speed, generator can be selected for the synchronous speed. In this paper, the inlet flow angle to the runner is taken as 16° according to Banki's design. When considering the design of runner, the curvature of blade, inlet blade angle, the pitch value and the thickness of blade must be considered. The thickness of blade depends on the diameter of the runner.

If the speed of turbine is too low, the speed increaser must be used to increase the speed. But it is necessary to consider not only the force of the water which strike the runner, but also own weight of the runner.

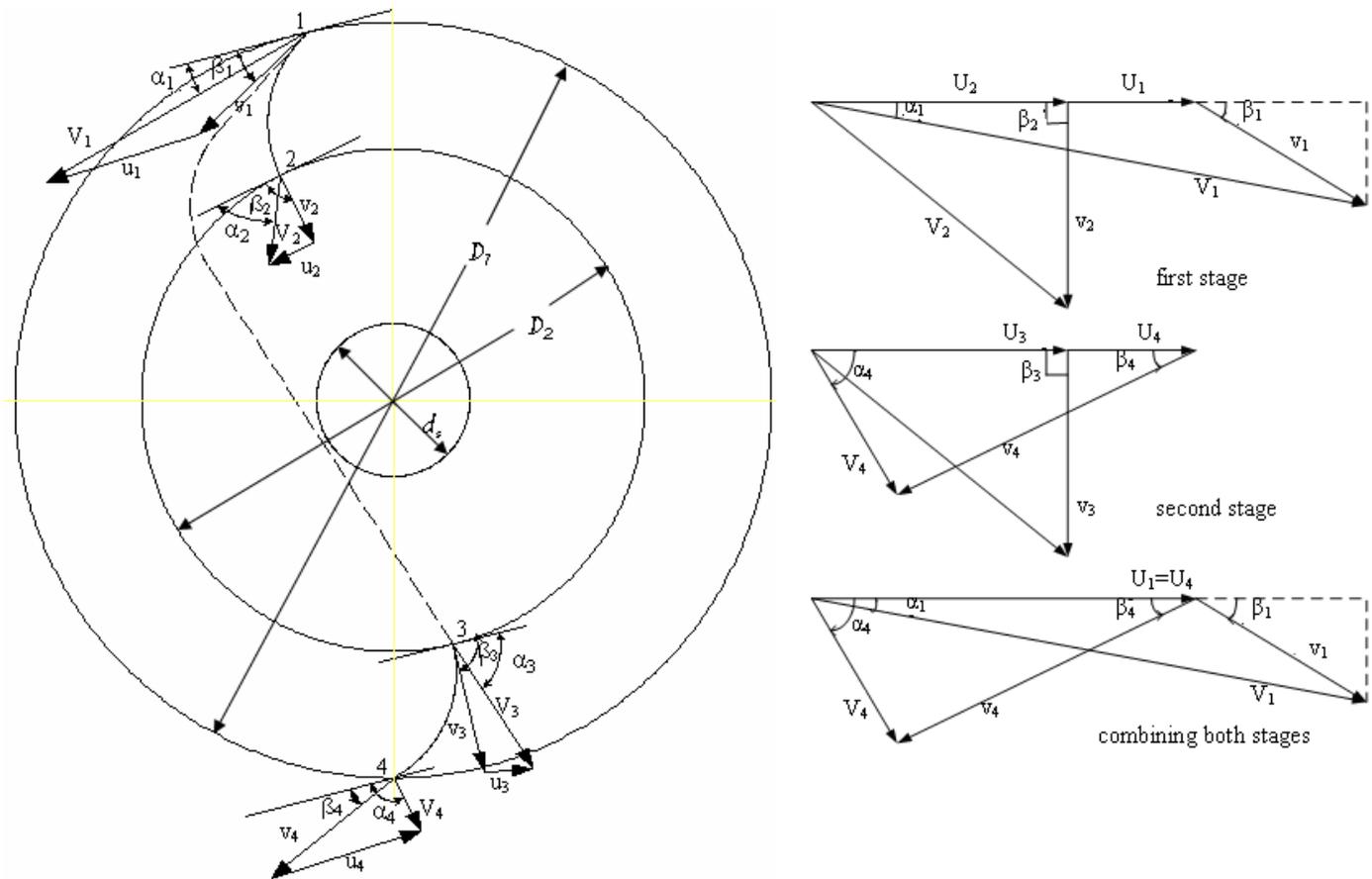


Fig.2 Water Flow Path through the Runner and Velocity Diagram [2]

According to this explanation, the entire flow that comes in from a part of outer periphery of runner to the first stage blades flows across the inner space at the center of runner than again flows out to the other side of outer periphery of runner via the second stage blades. The first stage turn-around flow is caused by a part of the flow along the upper portion of nozzle being unable to cross because of being pushed by the flow along the lower portion of nozzle. As a result, the flow at the nozzle outlet has considerable pressure and is not the free jet. There is also a measured data that the Cross-Flow accelerates from the first stage outlet to the second stage inlet in the inner space, so the velocity triangle of flow will not become homologous neither at the first stage outlet nor at the second stage inlet. The flow of Cross-Flow turbine is as complicated as mentioned that it cannot be treated as the simple impulsive flow [1].

III. DESIGN OF CROSS FLOW TURBINE

In this paper, the required design data are based on Chi Chaung Hydropower project in Chin State, Myanmar and design specifications are as follow.

Effective head, $H = 28$ m

Expected output power, $P = 100$ kW

Efficiency of turbine, $\eta_T = 80\%$

Efficiency of generator, $\eta_G = 95\%$

Overall efficiency, $\eta_o = \eta_T \times \eta_G = 76\%$

Density of water, $\rho = 1000$ kg/m³

Acceleration due to gravity, $g = 9.81$ m/s²

The 100 kW turbine is within the range of Mini-hydropower plant and the required flow rate of this turbine can be determined by using power equation.

$$\text{Flow rate, } Q = \frac{P_g}{\gamma H \eta_o} \tag{1}$$

By Equation (1), the required flow for expected output power is 0.5 m³/s.

A. Suitable Turbine Type Selection

Firstly, suitable type of turbine that will be used must be determined based on the design flow rate and effective head. According to the Fig. 3, the design turbine of effective head 28 m and flow rate 0.5 m³/s for the expected power 100 kW is within the ranges of Cross-Flow turbine type. Thus, for the design flow rate and head, Cross-flow turbine type is selected.

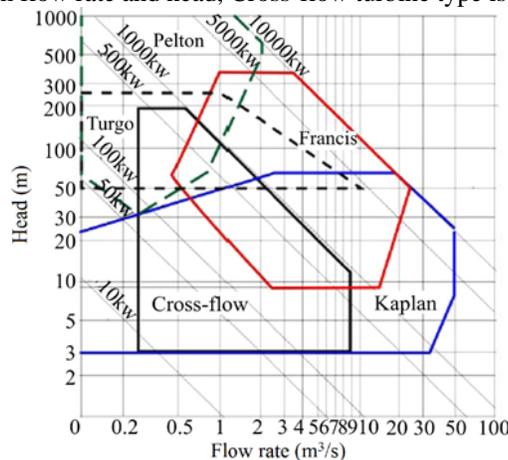


Fig. 3 Selection of Turbine Type [4]

B. Determination of Specific Speed and Rotational Speed

To determine the basic dimensions of turbine easily, the value of specific speed must be known. Specific speed of a turbine is the speed of a geometrically similar turbine which would develop unit power (metric) when working under a head of one meter. Specific speed also plays in an important role for the selection of turbine type. And also the performance of turbine can be predicted and the fundamental dimensions of the turbine can be easily estimated based on the specific speed value of turbine. For Cross-flow turbine, the range of specific speed is $40 \leq N_s \leq 200$ [2]. Applicable maximum specific speed is

$$N_{s\max} \leq 650 H^{-0.5} \tag{2}$$

The applicable maximum specific speed is 122.8 and specific speed formula by Kpordze and Warnick, 1983, is

$$N_s = \frac{513.55}{H^{0.505}} \tag{3}$$

The calculated specific speed, 95.39 is within the range 40 and 200, and less than the applicable maximum value of specific speed 122.8.

The rotational speed of a turbine is directly relative to its specific speed, flow and net head. In the small hydro schemes, standard generators should be installed when possible, so in during turbine selection it must be considered that the generator either coupled

directly or through a speed increaser to the turbine, should reach the synchronous speed. The rotational speed of turbine is

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

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

$$P_o = \frac{120 f}{N} \tag{5}$$

Where, f is frequency (50 Hz).

C. Determination of Runner Diameter and Breadth

Runner is the main component of the turbine that converts water power to shaft power. So, the shape and dimensions of runner are very important in any turbine. For the maximum efficiency, η_{max} the periphery velocity of the wheel U is $0.5V$. However, in actual practice, the maximum efficiency occurs when the value of U is about $0.46V$. Therefore, the periphery velocity of the wheel can be determined as follow:

$$k_{u1} = \frac{U_1}{V_1} \tag{6}$$

$$U_1 = \frac{\pi D_1 N}{60} \tag{7}$$

$$V_1 = k_c \sqrt{2gH} \tag{8}$$

where,

k_{u1} = coefficient of rotational velocity (0.4 ~ 0.5)

k_c = coefficient of water velocity (0.92 ~ 0.99)

D_1 = diameter of runner (m)

When k_c and k_{u1} are chosen as 0.98 and 0.46 respectively, runner diameter D_1 can be determined by Equations (6), (7) and (8).

Breadth of the runner depends on the jet thickness and water inflow velocity. The thickness of the jet, S_o is 0.1 to 0.2 times of runner diameter. By taking the average nearly,

$$S_o = 0.17 D_1 \tag{9}$$

The total area of jet can be determined by using continuity equation,

$$Q = AV_1 = S_o \times L \times k_c \sqrt{2gH}$$

Thus, the breadth of runner is

$$L = \frac{Q}{S_o \times L \times k_c \sqrt{2gH}} \tag{10}$$

In this design, the runner has middle disk and the real breadth of runner must be added 10% more [2]. Thus, Real breadth of runner is

$$L_1 = L + 0.1 L \tag{11}$$

After determining the dimensions of runner diameter and breadth, it needs to check the ratio of runner breadth to runner diameter. Not to poor the runner proportions, this ratio must be within the following range.

$$0.16 \leq \frac{L_1}{D_1} \leq \frac{21.24}{H^{0.85}} \tag{12}$$

If this ratio isn't within the range, runner diameter or breadth must be increased or decreased by trial and error method until it is satisfied.

D. Required Parameters of Blade Curvature

The blade curve can be chosen from a circle whose center lies at the intersection of two perpendiculars, one to the direction of the relative velocity and other to the tangent to the inner periphery intersection. The drawing method of blade curvature is shown in Fig 4.

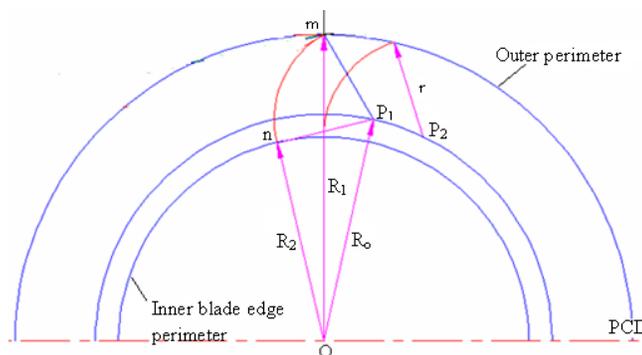


Fig 4. Curvature of Blade

Where, Outer radius of runner, $R_1 = D_1/2$ (13)

Inner radius of runner, $R_2 = D_1/3$ (14)

Radius of blade shaped arc, $r = 0.16 D_1$ (15)

Radius of circle of center pitch of shaped arc, $R_o^2 = R_2^2 + r^2$ (16)

Blade pitch, $P_1P_2 = \frac{2\pi R_o}{Z}$ (17)

The number of blades, Z is ($24 \leq Z \leq 30$) and the fewer blades may cause pulsating power, while a larger number of blades may cause excessive friction losses. So, the number of blades is chosen as 26 blades in this design.

E. Blade Thickness (t)

The thickness of the blade depends on the diameter of runner and the relationship between them is shown in Table I. In this design, the calculated runner diameter is 430 mm and so, the thickness of the blade is chosen as 6 mm.

Table I. Runner Diameter and Blade Thickness [2]

| | | | | | |
|-------------------------|-----|---------|-----|-----|------|
| Runner Diameter (mm) | 200 | 300 | 450 | 700 | 1000 |
| Thickness of Blade (mm) | 3.2 | 4.5 ~ 6 | 6 | 9 | 12 |

F. Prediction of Shaft Diameter

The turbine shaft will transmit the rotary motion of the runner to the generator via the drive system. 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 shaft diameter is estimated by

$$d_s = 150 \sqrt[3]{\frac{P}{N}} \tag{18}$$

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

G. Determination of Penstock Diameter and Thickness

The required diameter of penstock (d_p) can be estimated by the following equation.

$$d_p = \left[\frac{Q}{0.785V} \right]^{0.5} \tag{19}$$

where,

$$V = 0.2 \sqrt{2gH}$$

Q = discharge in the penstock (m^3/s)

V = velocity of water in the penstock (m/s)

The thickness of penstock (t_p) should be greater than 6 mm and it can be determined by the following expression.

$$t_p = \frac{d_p + 800}{400} \tag{20}$$

IV. RESULTS OF RUNNER DESIGN

Table II. The Calculated Result for Cross-Flow Turbine

| Descriptions | Symbols | Value |
|--------------|---------|-------|
|--------------|---------|-------|

| | | |
|----------------------------------|----------|---------|
| Power | P | 100 kW |
| Breadth of runner | L_1 | 415 mm |
| Diameter of runner | D_1 | 340 mm |
| Internal diameter of runner | D_2 | 227 mm |
| Radius of blade shaped arc | r | 54 mm |
| Radius of circle of center pitch | R_o | 126 mm |
| Blade pitch | P_1P_2 | 30.4 mm |
| Blade thickness | t | 6 mm |
| No. of blades | z | 26 |
| Diameter of shaft | d_s | 90 mm |
| Diameter of penstock | d_p | 400 mm |
| Turbine speed | N | 600 rpm |
| No. of pole | P_o | 10 |
| Expected Efficiency | η | 88 % |

The calculated results of especially runner design for 100 kW Cross-flow turbine based on head of 28 m, water flow rate of 0.5 m³/s and turbine rotational speed of 600 rpm are clearly expressed in Table II. Moreover, detail drawings of blade curvature and runner design are also shown in following figures.

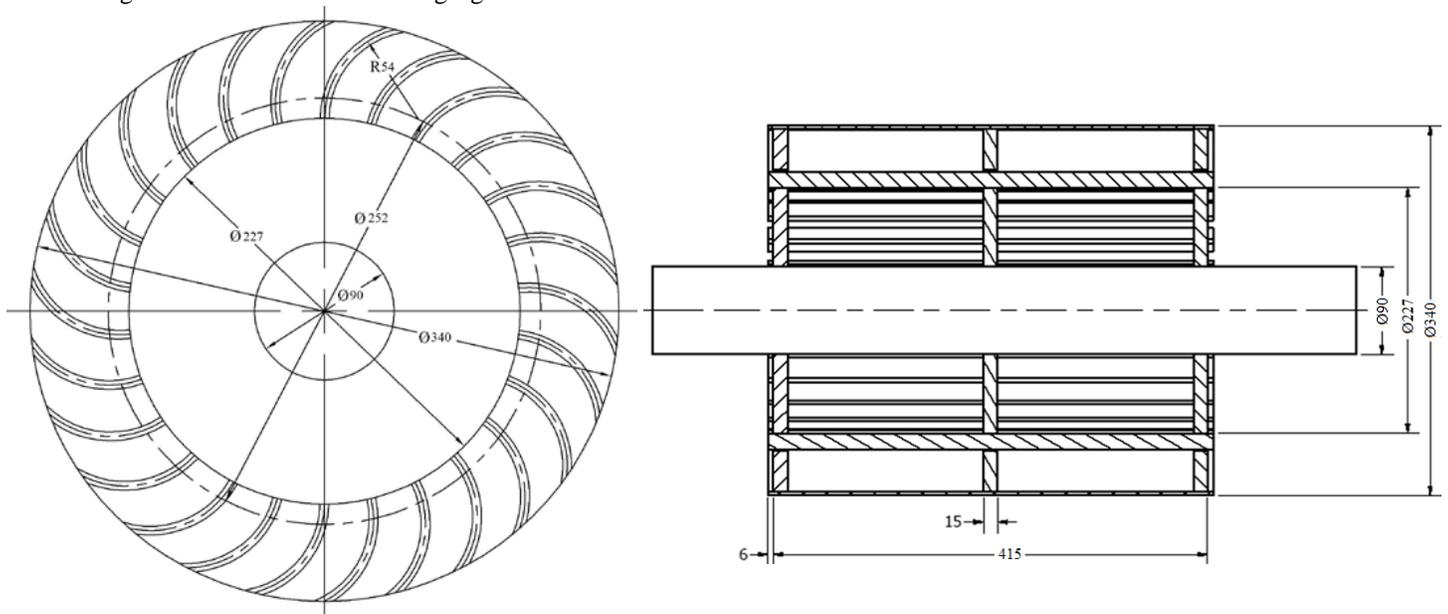


Fig 5. Side View and Front View of Runner

| Parts List | | |
|------------|-----|-----------|
| ITEM | QTY | PART NAME |
| 1 | 1 | SHAFT |
| 2 | 3 | DISCK |
| 3 | 26 | BLADE |

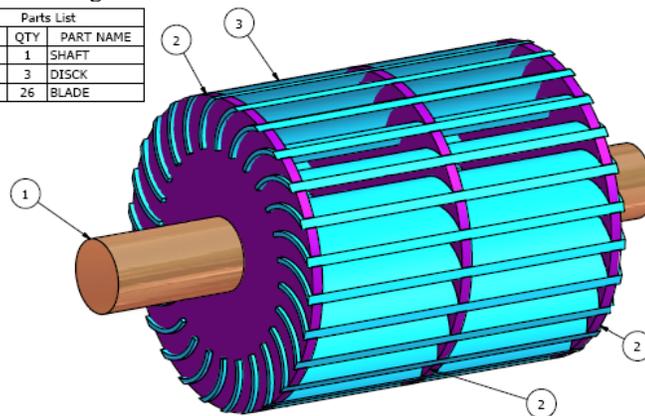


Fig 6. 3DView of Runner

V. ANALYSIS OF RUNNER'S DIMENSION AND OUTPUT POWER

In this studying, runner diameter and breadth and output power are analyzed by varying flow rate and head. The range of flow rate is from 0.2 to 1 m³/s and the range of head is from 10 to 50 m.

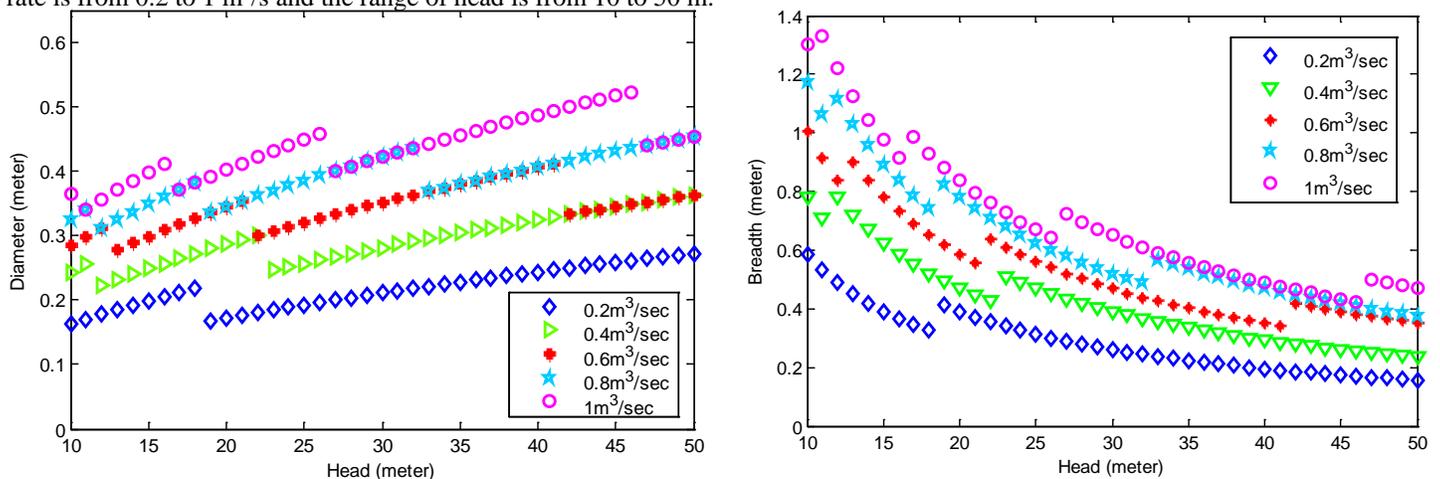


Fig 7. Runner Diameters and Runner Breadth on Various Head and Flow Rates

VI. CONCLUSION

For high demand electricity, the Cross-flow turbine is used for rural areas and the place which is far from the grid system. It can be used for low and medium head of water using simple technology that can be locally designed and easily built, with mainly local materials at low cost. In this paper, Cross-flow turbine is designed for 28 m of head and 0.5 m³/s of flow rate to generate 100 kW. To design the runner, some parameters of Cross-flow turbine are assumed. In this design, the water inlet flow angle to the wheel is taken as 16° to get optimal efficiency according to Banki's design. By using this inlet flow angle, the inlet blade angle has been determined. The diameter of the designed runner is 340 mm and the breath of runner is 415 mm. In this turbine, the number of blade is 26 and the thickness is 6 mm. The blade can also be cut out of thin-wall tubes, or made of strips of thin sheet metal rolled around a pipe. The diameter of shaft is 90 mm and penstock is 400 mm for this turbine. A synchronous generator 10 pole will be used by the direct coupling system. Moreover, diameter and breadth of the turbine runner are also analyzed by varying the head and flow rate. In this studying, the varying head range and flow rate range are from 10 to 50 m and from 0.2 to 1 m³/s respectively. Because of this analyzing, the suitable runner's diameter and breadth can be chosen easily within these operation ranges for cross flow turbine type.

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