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Design Optimization To Increase A Cross Flow Turbine Performance: A Review

Rudy Soenoko
Brawijaya University, Mechanical Engineering Department, Engineering Faculty, 615145 Malang Indonesia
rudysoen@ub.ac.id

Abstract
A cross flow turbine is a typical turbine used in Indonesia for micro-hydro power plant. It is seems that that there are two major weaknesses to this type of turbine design. The first weakness is the number of blades hit by the water jet on the first level. The water speed output from the first level would result a different direction and will lead the water flow collide one to the other. It will lead a chaotic water jet direction getting into the turbine blade second level. The second weakness is that the water jet stream getting in the first turbine blade was controlled by a guide vane. This water controlling system will lead a flow disruption that the water flow jet direction would always change for each guide blade position. These weaknesses will lead a poor cross flow turbine performance, the turbine efficiency would be very low. The turbine rotation setting would be very difficult during the turbine operation the turbine rotation would not be constant. To improve the performance of the turbine, there are some suggestions for the turbine performance improvements, which are modifying the water flow nozzle construction, optimizing the nozzle position and blades number to be hit by the water jet from the nozzle. Based on the modification suggestions, a new design steps has been made.

Keywords: Cross flow turbine, weakness, optimization, nozzle position

Introduction
Even the complex problems experienced by large industry can be solved the world is still lack of energy. This problem is particularly keenly felt in developing countries where people living in the village require the development of more efficient energy sources. The more expensive and limited fossil fuels, makes the energy from hydropower be the best alternative. A survey results were reported that on the end of 2010, hydropower use to generate electricity is about 3,427 terawatt-hours which is about 16.1 percent of the world electricity consumption, and would continue with an increase about 3.1% each year [1, 2]. There is still a lot of untapped hydro power including low head hydropower, which is located in developing countries that electricity is really needed.

Cross Flow Turbine
Until to now, there is still a lot of micro-hydro project using water wheel as their prime mover to harvest the water potency to be converted to electricity. Lately the focus is shifted to the cross flow turbine type especially for small hydro projects in development countries. Therefore it is interesting observe the cross flow turbine potency. The simple design form, causing it easy to understand how it works and the easier it is made in a simple workshop. The National Rural Electric Cooperative Association reported that the current cross flow turbine type have been installed in some rural areas and isolated areas in Pakistan, Nepal, Peru, the Philippines and Thailand [3, 4].

Benefits
There are five benefits when using cross flow turbines as a prime mover. Firstly, the nozzle and the disc can be made from steel plate and blades can be made from pieces steel pipe, so that the turbine construction and the turbine design become very simple. Secondly, cross flow turbine could have an excellent efficiency curve, especially when using a guide blade division system. This is particularly important for the turbine installed on a low head waterfall. Thirdly, the initial investment cost of making a cross flow turbine is much cheaper compared to the investment cost of other types of turbines used for low head hydro-power system. The maintenance costs, operating costs and the civil construction cost is also lower compared to other types of turbines. The forth benefit, is that dirt or impurities passing through the blade will easy to leave the turbine rotor, on a half turbine rotation this dirt will be thrown off by itself, by the centrifugal force. Finally, is that cross flow turbine rotation area is suitable for the use of driving electrical generators, driving corn mills, chainsaws and pumps.
Representatives of more than 170 countries reached consensus at the Top World Conference on Sustainable Development, in Johannesburg (2002), and at the 3rd World Forum on Water, in Kyoto (2003): all hydroelectric generation is renewable and merits international support. [5, 6, 7]

Cross Flow Turbine Principle
A Cross flow turbine is a turbine where the rectangular cross sectional nozzle spraying a water jet with a certain water flow rate getting in blades mounted around a cylindrical rotor. Water speed energy is given to the rotor blade in two stages. The first energy given is when the water passes through the rotor from the nozzle, and the second energy given is when the water hitting the other blades before leaving the turbine disc rotor. Water enters the runner, flowing from the outside to the runner center and provide about 70-80 % of its energy (3, 4). After going through the inside part of the runner then the water will hit the next blade from the inner side of the runner and would give another about 20-30% of energy to the turbine runner. A Cross flow turbine is equipped with a nozzle, runner and a draft tube.

Nozzle

Water flowed into the runner through a nozzle which is generally has a rectangular shape. The regulating blade mounted inside the nozzle would control the flow area start from the maximum area until to zero. Blade shaft is made in such a way that the hydraulic torque that occurs as small as possible. The guide vane could be used to close the water flow completely with a condition that the head is not more than 50 m. To shut the water flow off on a more than 50 m head a cover valve is needed. The vane guiding rotary movements could be done by a regulatory arm which is connected to an automatic or manual system. Nozzle changing the total water energy flow into kinetic energy. Furthermore, this nozzle directs the water into the blade at a very small water flow angle of about 15° [8, 9].

Runner

The cross flow turbine runner has two main parts. The first part is the blade, where the blade is converting the kinetic energy of water flow to the turbine runner. These blades are curve shaped and mounted fixed on the parallel frame runner to the axis of the turbine shaft. The blades is formed in such a way that when the water leaves the blade, the water flow would continue to have a significant kinetic energy. So the water flow jet is twice going through the runner blade. The blade number on the turbine runner could reach up to thirty pieces, depending on the turbine runner size. The second part of the runner is the turbine disc or runner frame. There must be a minimum of two discs (disc) in a cross flow runner, where the blades will be welded around the disc, with an equal distance one to another.

Draft Tube

The draft tube installation at a cross flow turbine is to obtain effective head as much as possible, by utilizing the static head under the turbine and the turbine head water kinetic coming out from the turbine. Setting the pressure in the draft tube is important especially for turbines that have a very low head by controlling a wide area. Air valve on the turbine housing will help to set the vacuum pressure that occurs in the draft tube, so that a low head turbine can operate at an optimum efficiency.

Cross Flow Turbine in Indonesia

Indonesia stretches from west to east over approximately 6,000 kilometers and has approximately 13,000 islands. The population of Indonesia is approximately 249, 8 million people on 2013, where 80% of the total number living on the island of Java [10, 11]. The electrification ratio figure in Indonesia is around l6%, this is the highest figure. So it is still very small amount of Indonesian population that could enjoy electrical energy [12]. 80% people in Indonesia live in rural areas where the availability of electricity in rural areas is very low, so the need for electricity will be a very urgent need.

Energy utilization of water in rural areas in Indonesia has been quite a lot. Water mill was used for grinding corn or to pump water from a certain height. Hydraulic ram (self-action pump) is also used to pump water. Another way to harness the water energy is by utilizing micro hydro to generate electricity or mechanical power.

Cross flow turbine has been widely used for micro-hydro projects in Indonesia, but a lot of problems that arise in such projects. One of the causes of the problem in question is the poor turbine design. As mentioned above, the first weakness in the cross flow turbine is the consideration of the number of blades to be hit by a water jet (jet entry arc). As a result of these considerations it would rise to three main problems. The first problem is the jet direction for each blade will be different from one to another, in the calculation of the jet direction to the runner for each blade (α_1) are considered to be equal.

The second problem is that the water flow out from the first level will collide one to another, which is assumed in the calculation no collision occur. The third is the less precise assumptions about the width of the water jet (jet) coming out from the first level blade, which would result an inaccurate relative water jet direction (w_2) which is less precise anyway.

The second weakness is the nozzle construction which is fitted with a regulator blade.

The blade regulator installation is for adjusting and synchronizing the turbine rotation by adjusting the water speed and the jet water flow rate. This system is not good because the water jet direction would always change exactly in line with the blade regulator position. The turbine rotation arrangement becomes very difficult especially for the exact turbine rotation, it takes time to achieve a desired rotation would be long enough.

Purpose of Study

The main objective of this study was to observe the cross flow turbine weaknesses in Indonesia and discusses these weaknesses theoretically within the design system.

Furthermore, based on the discussion results, a new cross flow turbine planning sequences could be arranged. Lastly, evaluate the old and new design differences based on some design theory.

Method

The method used is literature study and discussion is done theoretically.

Important Factors

In planning a cross turbine flow several factors should be considered, where these factors will affect the outcome of the cross flow turbine design. The better the design the more stable the cross flow turbine rotation, the more easy to operate and of course the better the efficiency.

Jet width

According to the continuity law, the water flow rate passing through a cross-section will always be constant, which means that the number of incoming water is equal to the amount of water coming out. This applies to water that passes through

the blades of a cross flow turbine. The width of the cross flow turbine nozzle is the width of the tip end of the nozzle which have a rectangular shape (= f), where the water jets leaving the nozzle and then enters the turbine runner (Fig. 1).
There are two possibilities of nozzle width selection. First, is based on the nozzle width, which is the biggest blade spacing (the outermost runner), with the consequence that the water flow rate in the outer part of the blade would rise. Second, is to choose the nozzle width based on the smallest blade space, where on this nozzle condition the output water speed would be equal to the water speed entering the blade [13].

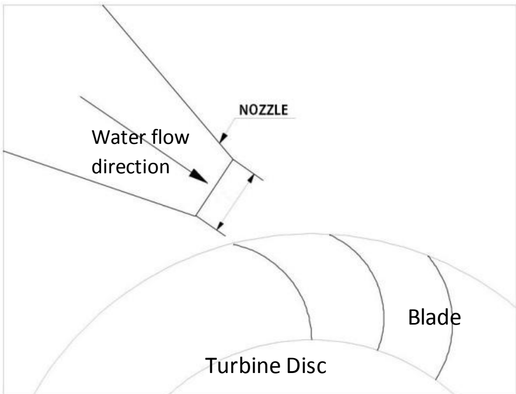

Fig. 1: Nozzle Width

Triangle Velocity

Fig. 2 shows a cross flow turbine rotor which is completed with a triangular velocity. In the triangle speed there are three velocity components. The first velocity component is the tangential velocity u, which is the peripheral speed of the rotor. Second, is the water flow speed or absolute velocity v, and the third is the water velocity relative to the blade or the so-called relative velocity w. Every water flow point on the waterways has a triangle speed. The speed components each point is marked by the subscript velocity component. For example, the tangential velocity on the first level inlet (inlet inward passage) is u_1, the relative speed at the inlet of the first level is w_1.

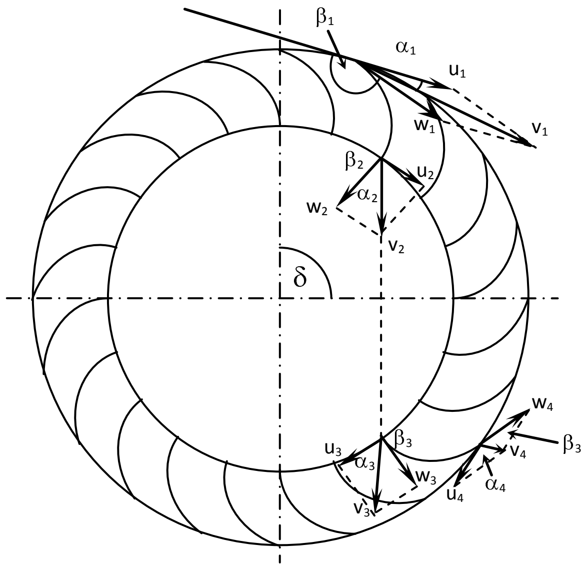

Fig. 2: Cross Flow Turbine Triangle velocity

To determine the velocity components in the triangle velocity, the outlet speed determination at the first level w_2 (outlet inward relative velocity) must be chosen very carefully. If the w_2 assumption is not accurate then the whole turbine design will not be accurate anymore. The irregularities that occurred at the beginning of the calculation assumptions would certainly be greater at the end of the planning.

The jet maximum width

The maximum width of the jet meant here is the jet width based on the distance between the two blades. The maximum jet width selection should be done carefully because the maximum distance of two blades is not the distance between the two ends of blade x, but it is **a** (Fig. 3.).
On the maximum jet width selection the relative velocity w_2 out from the first stage (level) will be greater than the relative speed of water entering the first stage w_1. If it is assumed that the first stage out absolute velocity v_2 have the same magnitude and direction with the absolute speed v_3 enters the second level, then the relative velocity out from the first stage w_2 has an equal magnitude and direction with the relative speed getting in the second stage w_3 [14].

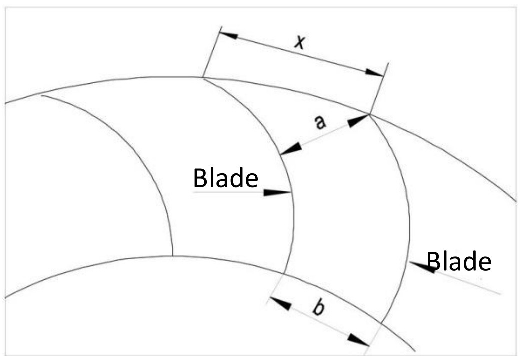

Fig. 3: Distance between two blades

The relative velocity on the second stage output w_4 would always be equal to the input relative velocity on the second stage w_3, this is because of the input cross sectional area on the second stage is smaller than the cross sectional area on the discharge side.

$w_1 < w_2$ (1)

$w_2 = w_3 = w_4$ (2)

Where:

w_1 = the relative velocity of water on the first stage inlet
w_2 = the relative velocity of water on the first stage outlet
w_3 = the relative velocity of water on the second stage inlet
w_4 = the relative velocity of water on the second stage outlet

The jet minimum width

For the jet minimum width selection, the jet width taken is equal to the smallest distance between two blades. (= B Fig. 3). This minimum jet width selection is based on the equal relative velocity magnitude on the first stage input w_1 and the first stage output w_2.

For a maximum turbine performance it is assumed that all of the relative velocity magnitude should be equal, so the relative velocity w_1 should equal to the relative velocity w_2, it is also equal to the relative velocity w_3 and relative velocity w_4 ($w_1 = w_2 = w_3 = w_4$).

Basically for the jet width minimum and maximum selection there is no significant difference, but these differences will greatly affect the turbine design. Many errors were found in the cross flow turbine design especially related with the turbine relative velocity.

One example of the inaccurate assumption is that $w_1 = w_2$ M (this assumption is adopted from the triangle velocity), where M is the ratio between the inner diameter and outer diameter that is b/x (Fig 3.). This relationship is obtained, as it is considered that the maximum distance between two blades is x, whereas the actual maximum distance is a.

Jet entry arc

The cross flow turbine nozzle width is as wide as the runner width (distance between two discs), where the arc around the rotor should mounted as close as possible to reduce the water flow leakage. δ is the jet entry arc angle, most cross flow turbines $\delta = 90°$ (Fig. 4) [15].

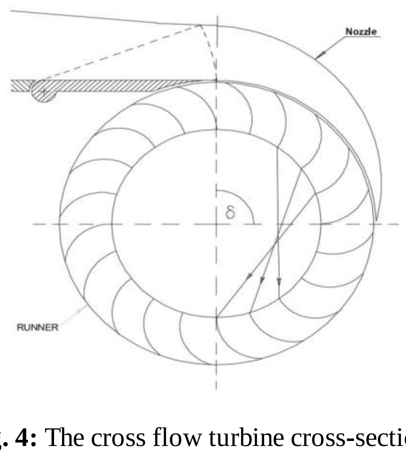

Fig. 4: The cross flow turbine cross-sectional

Weaknesses

Cross flow turbine designs used in Indonesia is described in the diagram in Fig. 4. As mentioned above that this cross flow turbine design has many weaknesses.

The first weakness

As already mentioned, that the consideration of the number of blades hit by the nozzle jet is one of the weaknesses of the current cross flow turbine design. This occurs because of a certain entry arc jet $\delta = 90°$ (Fig. 4). As a result, there will be some deviation in the turbine design.

The first deviation is that the incoming jet angle for each blade will be different from each other. The nozzle shape would not be able to guarantee angle as precise as in the design calculation for each blade. In the design calculation, the triangle velocity was taken account for just one blade, wherein the other blades are presumed to have the same condition.

Due to the multiple blades hit by the water jet, the water coming out from the first stage would collide one to another, this is one of the causes of the unstable turbine rotation and as a consequence is that there is no additional power produced at the second level.

This problem can be solved by installing a directional channels in accordance with the direction of the water obtained from design calculations, but the construction is very complicated (Figure 6).

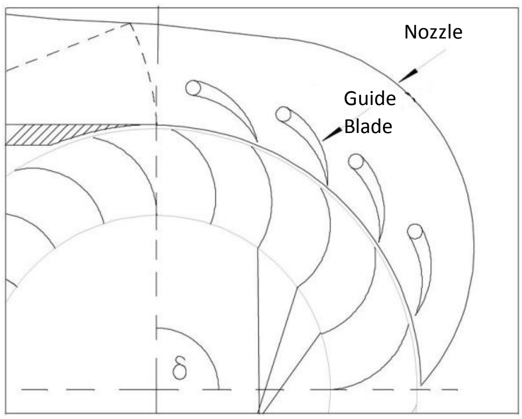

Fig. 5: Nozzle with guide blades

Another way is to set the direction of each jet entered in such a way, for example by installing a regulator blade where each blade could be move separately so that the water flow out direction could be controlled to be align. This system can only be used in certain circumstances, if the conditions change, the situation will turn into chaos.

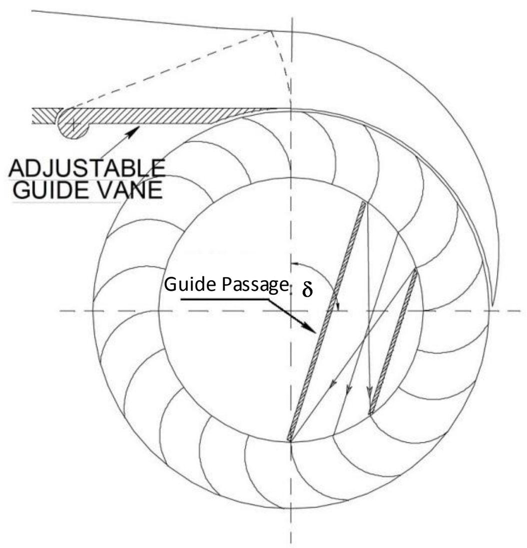

Fig. 6: Nozzle with a guide passage

So the water flow pattern when the turbine operates is different from the expected water flow pattern on the design. This problem could be solved by putting some guide blades in front of each turbine runner blade similar as in a Francis turbine, but the cost would be high and the turbine design becomes complicated (Fig. 5).

As mentioned before that the water out flow from the first stage collide each other (Fig. 4), would resulted in irregular water flow entering the turbine second stage, and there would no energy or power addition. This happens because the water flow collides freely in the air, without any duct or pipe that directs water that collide this [16].

Another solution suggested to solve the irregular water flow problem on the first stage output is by attaching a guide passage to guide the output water from the first stage to be regular, and could hit the second stage on an optimum angle of attack to produce another power addition.

This can be explained by reviewing the relationship between the turbine rotation (n = rpm), the tangential force (P) and torque (T). The relationship between torque, power and rotation is as follows:

$N = (T \times n) / C$ (Black, PH) (3)

and the relationship between torque and force are as follows:

$Q = P \times R$ (3) (4)

To drive an electric generator a turbine as a prime mover should have a constant rotation, either on a constant or on a variable the load changes. So when the load change and not being constant the turbine rotation should remain be constant then the only way is to change the turbine torque (formula 2). Torque could be changed by changing the potential force P (formula 3), which is by regulating the water jet speed. The main thing to be remembered is that the jet speed change means a change on the triangle velocity.

The second weakness

The water jet flow from the nozzle is controlled by a regulator blade (Fig. 5). The regulator blade is driven up or down according to the requirement (8). The weakness of this system is, the water flow disruption and the jet direction would always change for each blade position. J. van Berkel, in his article on "Modeling an adjustable nozzle for the cross flow turbine" [17], proposing a new design for a cross flow turbine nozzle, with this design it is expected to reduce the nozzle loss. The basic water flow regulation in the nozzle is a butterfly valve. It is expected that the whole potential energy is being converted into kinetic energy.

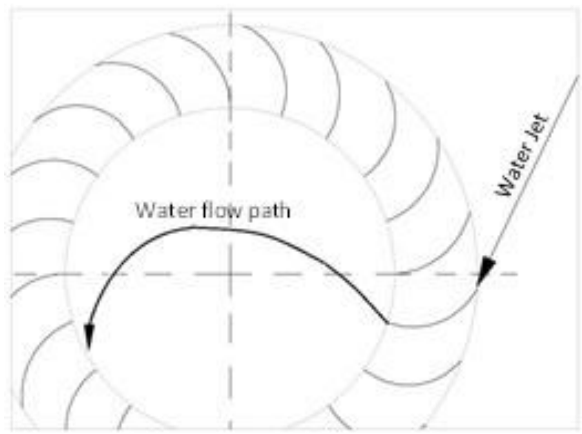

Fig. 7: Water flow path on a cross flow turbine flow

Secondly, set nozzle at a certain position so that the water flow direction flowing out from the first stage (v_2) being parallel to the turbine vertical axis. The reason to use this strategy is to avoid or minimize the parabolic water flow path due to gravity (illustration Fig. 7). A parabolic water flow path could reduce the power generation on the second stage (eg $\alpha_3 > 90$).

It is expected that the water flow could follow in a straight line path, so that the turbine design condition could be similar to the actual turbine operation condition.

The third is, modifying the nozzle construction, to ease the controlling of the water velocity coming out from the nozzle without disturbing the water jet direction then it should be the nozzle construction based on the Pelton nozzle design (Fig. 8).

For the nozzle width selection it is better to choose the minimum suggested size. The reason to choose this minimum size is for the ease of the calculation of turbine, planning and producing.

Nozzle position

One of the strategies in this article to get the maximum cross flow turbine performance is setting a certain nozzle position so that the v_2 direction is parallel to the turbine runner vertical axis. To obtain these conditions the γ angle (Fig. 8) must be set as follows:

$$\gamma = 180° - (\alpha_1 + \beta_1 + \alpha_2 - \theta) \quad (5)$$

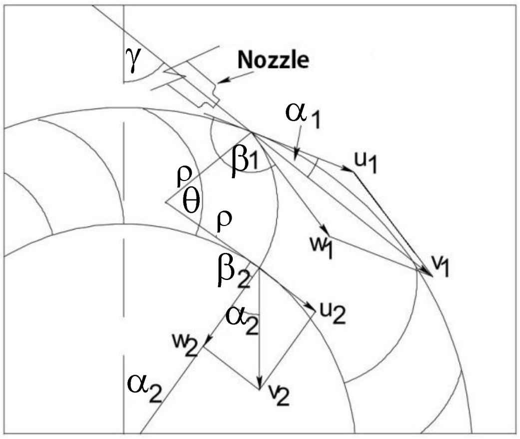

Fig. 8: The nozzle angle γ position

Conclusions

The difference between the old turbine design and the new turbine design is on the nozzle shape and the nozzle working system. The purpose of this modification is to facilitate the ease of jet speed settings and jet direction.

The differences on the new turbine design are as follows:

1. Only one blade pounded straight by jet.
2. There is no jet entry arc selection.
3. For the new design u_2 = arctan (u_2/w_2), while on the old design α_2 = arctan [(1/M). Cos (180° - α_1)]
4. The rotor with B = Q/(v_1 . t_2) while for the old design B = Q. (Z/I) {1/(π . D_1. v_1. sin α_1)}
5. The nozzle axis position toward upright rotor axis r is $\gamma = 180° - (\alpha_1 + \beta_1 + \alpha_2 - \theta)$

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