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Original Article

ANALYSIS OF CROSS FLOW TURBINE PERFORMANCE WITH GUIDE PASSAGE GATE VANE (GG) AT RUNNER TURBINE BY USING A TRIANGLE VELOCITY METHOD

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ABSTRACT

The aim of this research is to analyze the power produced by a cross flow turbine with the addition of Guide Passage Vane Gate (GG) on the turbine runner. The analysis uses a triangle velocity method. Guide Passage Vane Gate (GG) will direct the water jet coming out of the first-stage blade geared to the second stage.

This research uses a triangle velocity method, which consists of tangential velocity (u), relative velocity (w), and absolute velocity (v). Triangle velocity was analyzed at the first and second stage of turbine blade both by using the guide passage vane gate and without using a guide passage gate vane. The triangle velocity depiction begins with a collection of field data, i.e. the turbine rotation data. The turbine rotation without a guide passage vane gate is about 1215 rpm while the turbine rotation by using a guide passage vane gate is 1348 rpm. Lastly, the turbine tangential velocity (u), the turbine relative velocity (w) and the turbine absolute velocity (v) were analyzed to obtain the turbine power.

The result showed that the cross flow turbine triangle velocity using a guide passage vane gate, would increase the turbine power about 14024.18 watts or 13.4%. This result suggests that by using a guide passage vane gate, the water jet coming out from the first stage turbine blade has been directed to the turbine second stage and there is no water flow intersection.

KEYWORDS: Tangential Velocity, Relative Velocity, Absolut Velocity, Flow Rate, Mass Flow Rate, Turbine Force, Guide Passage Vane Gate & Turbine Runner

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INTRODUCTION

From previous laboratory studies, it can be concluded that by adding a directional path on several blades, the flow of water out from the first level will lead exactly to the second level blade inlet. The turbine rotation would be more stable. This is important for the electric generation quality. The guide passage attach on a cross flow turbine would increase the turbine efficiency as big as 11.118%, and increase the turbine power by 10%. Nozzle guide vanes with a second level increase turbine efficiency by 11.118%, and increases the turbine power by 10%. It is seen that there is a tendency of turbine power increase at every test with a constant turbine rotation of 300 rpm **[□]**. Many studies were done in the past for different parameters in a cross-flow turbine. Efficiency of the turbine was found to be in the lower range. CFD analysis is done for performance analysis of cross-flow turbine with variation in shaft diameter. From the results, it is found that on decreasing the diameter of the turbine shaft, pressure is found to be decreasing at the nozzle inlet. A maximum power output is obtained when the shaft diameter approaches zero value. Hydraulic efficiency of cross-flow turbine is found to be inversely proportional to shaft diameter. The increase in the value of hydraulic efficiency is about 5% when there is no shaft present as compared to the case when there is a shaft of 50 mm diameter inside the runner **[□].** The gate vane passage guide addition in the middle of the turbine runner increases the turbine efficiency about 9.8%. The turbine rotation with a gate vane passage guide reaches a rotation of n = 1348 rpm; for the turbine without a gate vane passage guide vane produces a turbine rotation n = 1215 rpm. The power generated for the turbine uses the gate vane guide passage P = 143588.35 watts, and the turbine without a vane produces a power about 128609.10 watts. The gate vane guide passage addition has increased the turbine power of 13979.25 watts, which is about 9.8% **[3].**

A newly developed air suction method for cross-flow hydro turbine is suggested in this study. The effects of air trapped located in the runner center would affect the cross flow turbine performance. The result shows that the air trapped in the runner would strongly affect the turbine performance considerably. The water passage installed in the turbine runner would significantly prevent the water shock loss at the runner axis and suppressing the water recirculation flow in the runner.

The air suction hole location on the turbine chamber wall is a very important factor for the turbine performance improvement. Moreover, the ratio between the air from the suction pipe and water from turbine inlet is also a significant factor of the turbine performance **[4].** Using a CFD analysis, nozzel shape, runner blade angle and runner blade number are closely related to the performance and internal flow of the turbine. Moreover, air layer in the turbine runner plays very important role in improving the turbine performance **[5].** Another effort to improve the cross flow turbine design, is to design the cross flow turbine based on the turbine triangle velocity. Furthermore, produce the cross flow turbine parts, based on the triangle velocity design. Conduct a research for this kind of cross flow turbine, and concentrate on the runner design and the turbine nozzle shape **[6].** From the above description, the research will be done by adding a Guide Passage Gate Vane in the middle of the runner turbine by removing the axis in the middle runner. The function of the Guide Passage Gate Vane is to direct the jets of water from the first stage to the second stage more directionally and not intersect in the middle of the runner. The addition of Guide Passage Gate Vane (GG) in the hope of getting a more stable turbine rotation and resulting in a much higher efficiency compared to current turbine current turbines. The stability of this round is required for the quality of electricity generated much better. The analysis will be used in this research using triangle velocity analysis.

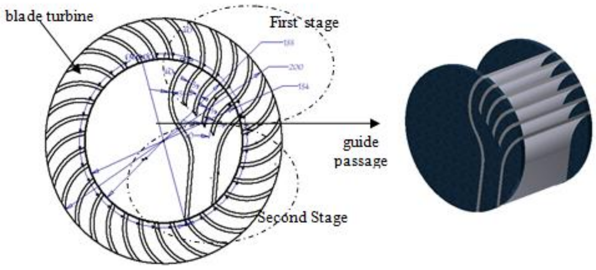
Triangle velocity is the basic kinematics of the water flow (fluid) which strikes a turbine blade. The understanding triangle velocity will be very helpful in understanding the process of converting the water turbine blades.

Each point of the water flow (fluid) on the drains has a triangle velocity. A review of the triangle velocity needs to be done earlier. The reasons to review the turbine triangle velocity is because there is a possibility of water entering the turbine flow line, either at the time of the first level and second level entry, is not as ideal as depicted in the triangle velocity. Which needs to be observed is whether the water jet entering the turbine second level would increase the turbine power or not. Does the water get into the second level reduce or burden the turbine runner. Because there is a possibility that the water jet entering the turbine second level is just hitting the blade back part. So that there is a reversal turbine rotation direction phenomenon. Therefore, instead of giving an additional turbine torque, a turbine torque reduction is obtained.

RESEARCH METHOD

Design Guide Passage Gate Vane used in this study consists of, holder, guide passage and gate vane. Design Guide Passage Gate Vane, consists of a holder of the guide passage gate vane, guide passage and gate vane *(figure 1a).* Guide Passage Gate Vane is made of stainless steel *(figure 1b).* The curvature of the Guide Passage Gate Vane is similar to the curvature of the turbine blade. Guide Passage Gate Vane is installed in the middle of the runner with a movable position *(figure 2).* Making a guide passage gate vane holder in the middle of the runner turbine is as follows:

- The holder on the left and right runner with a diameter of 20 cm, a thickness of 10 cm and a 13.5 cm inner diameter with a hole as deep as 5 cm.
- Then put the guide passage gate vane into the runner plate. The plate diameter size is 13.45 cm and the holder thickness is 5 mm.
- The diameter of the guide plate passage gate vane is smaller than the inner diameter of the runner turbine, with the aim that the guide passage gate vane can freely rotate in the middle of the runner turbine. The material used to make the guide passage gate vane is stainless steel (figure 2).



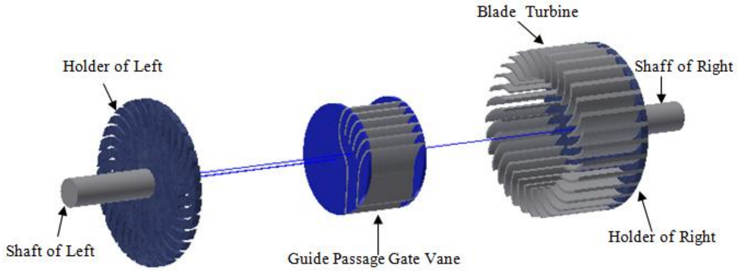


Figure 1:Guide Passage Gate Vane Design.
Figure 2: Guide Passage Gate Vane in a Turbine Runner.

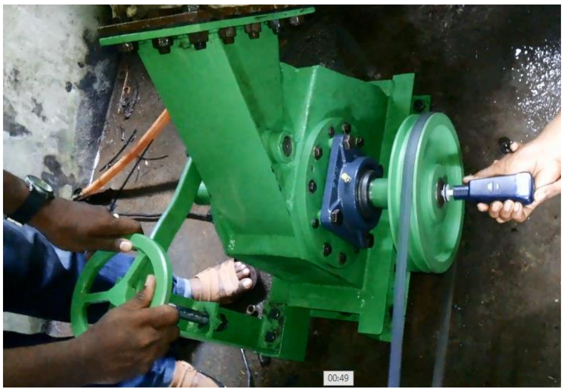


Figure 3: Turbine Rotation Measurement.

The turbine rotation data for both test runner models, cross flow turbine without a guide passage gate vane produce a turbine rotation of 1215 rpm, and the turbine cross flow with a guide passage gate vane produces a rotation of 1348 rpm (table 1, 2) (figure 3.)

Turbine rotation is needed as an initial data for the direction and the tangential velocity (u), then the absolute velocity (v) and relative velocity (w).

Table 1: Data Test without a Guide Passage Gate Vane

Flow Rate (m^3/sec)	**Turbine Rotation *(rpm)***
0,690	1215

Table 2: Data Test with a *Guide Passage Gate Vane*

Flow Rate (m^3/sec)	**Turbine Rotation *(rpm)***
0,690	1348

RESULTS

The jets of water from the nozzle into the first-stage turbine blades will rotate the runner turbine; then the incoming water jet to the guide passage gate vane is directed toward the second stage of the entry blade.

The initial data required for the triangle velocity analysis is the turbine rotation. The turbine rotation data is the turbine rotation without a guide passage gate vane and turbine rotation with a guide passage gate vane.

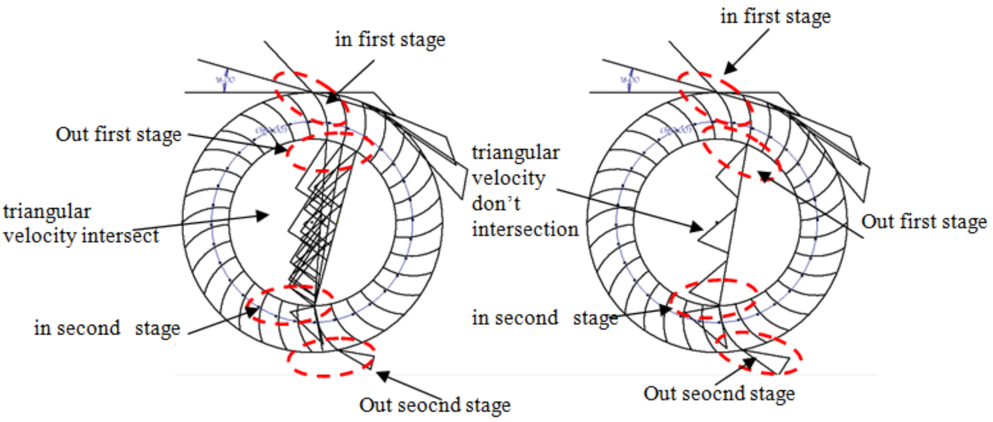
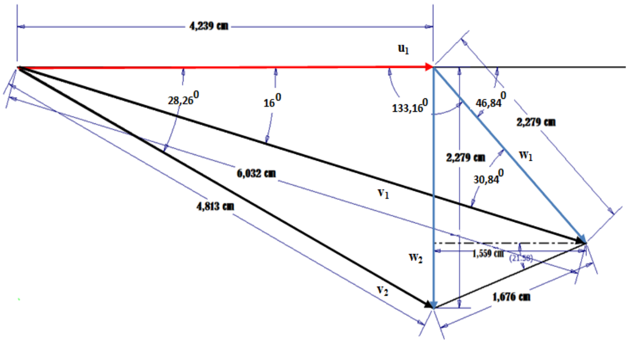


Figure 4: Water Jet Cross Flow Turbine Triangle Velocity on the Runner Turbine First Stage and Second Stage Illustration, (a). Without a *guide passage gate vane,* (b) Using a *guide passage gate vane*

The triangle velocity analysis is done in three steps, namely the first step when the water enters the first stage turbine, and leaves the first stage turbine. The second step is the analysis of water velocity leaving the first stage and then the third step is the water velocity, from the first stage output, getting into the turbine second stage. While the water velocity getting out from the second stage was not analyzed, because it was not utilized any further (Figure 3).

The water jet flow path through a cross flow turbine runner without a *Guide Passage Gate Vane* is shown in the figure 3 (a). The triangle velocity intersects in the middle of the empty space turbine runner. While in Figure 3 (b) where the turbine uses a guide passage gate vane, the triangle velocity that are produced do not intersect with each other, even the speed of the directional flow in the blade on the second stage. [1].

Furthermore, the triangle velocity plotting is done with 2 runner turbine models. First, is the turbine with a guide passage gate vane and second, is the turbine without a guide passage gate vane. The triangle velocity depiction is implementing the Autodesk Inventor 2008 software [7].

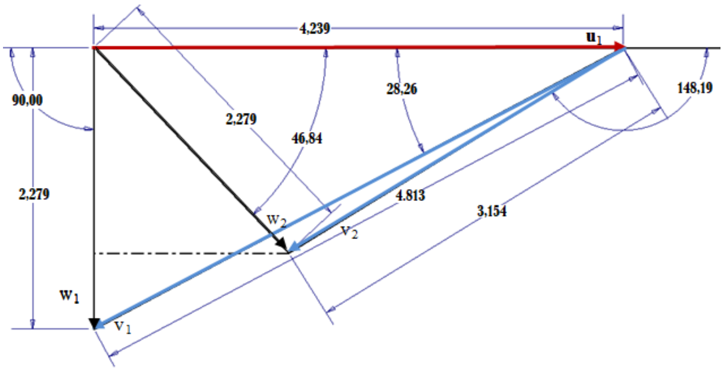


- ✓ Tangential velocity (u_1) = 12,717 m/sec
- ✓ Scale = 1 cm : 3 m/sec

Figure 5: The First Stage Triangle Velocity without a *Guide Passage Gate Vane.*

The first stage triangle velocity, without a Guide Passage Gate Vane.

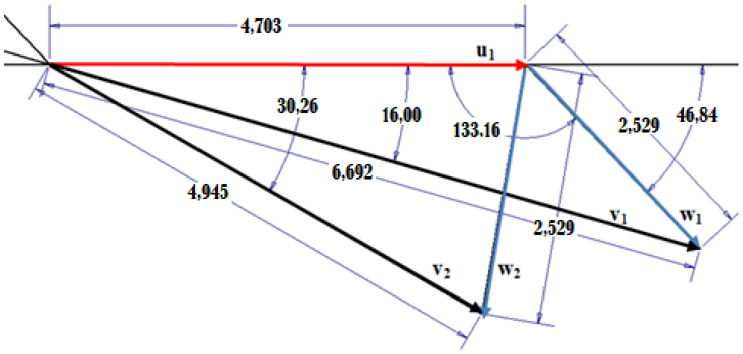
Triangle velocity on the second stage, without a Guide Passage Gate Vane.



- ✓ Tangential velocity (u_1) = 12,717 m/sec
- ✓ Scale = 1 cm : 3 m/sec

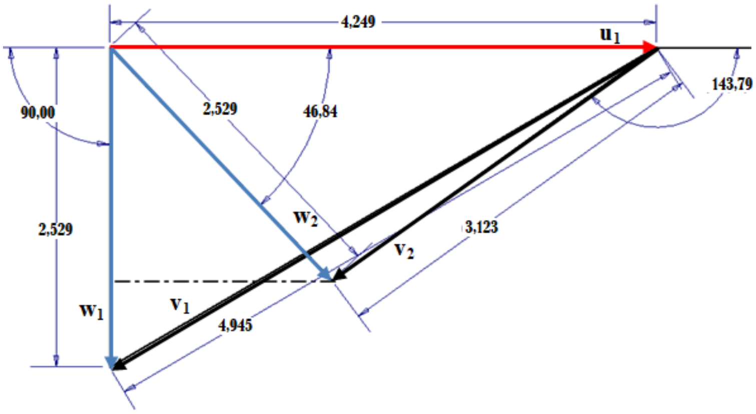
Figure 6: The Second Stage Triangle velocity, without a *Guide Passage Gate Vane* for a turbine rotation of 1215 rpm.

Triangle velocity on the first stage with a Guide Passage Gate Vane



- ✓ Tangential velocity (u_1) = 14,109 m/sec
- ✓ Scale = 1 cm : 3 m/sec

Figure 7: The First Stage Triangle Velocity with a *Guide Passage Gate Vane* for a Turbine Rotation of 1348 rpm.



- ✓ Tangential velocity (u_1) = 12,870 m/sec
- ✓ Scale = 1 cm : 3 m/sec

Figure 8: The Triangle Velocity Second Stage with a *Guide Passage Gate Vane* with a Rotation of 1348 rpm.

Table 3:The Triangle Velocity Data on the First Stage, without a *Guide Passage Gate Vane* for a Turbine Rotation of 1215 rpm

Velocity Direction	Line Length (cm)	Velocity (m/sec)
Tangential in (u_1)	4,239	12,717
Relative in (w_1)	2,279	6,837
Absolute in (v_1)	6,023	18,096
Tangential out (u_2)	4,239	12,717
Relative out (w_2)	2,279	6,837
Absolute out (v_2)	4,813	14,439

Table 4: The Triangle Velocity Data on the Second Stage, without a *Guide Passage Gate Vane* for a Turbine Rotation of 1215 rpm

Velocity Direction	Line Length (cm)	Velocity m/sec
Tangential in (u_1)	4,139	12,417
Relative in (w_1)	2,279	6,837
Absolute in (v_1)	4,813	14,439
Tangential out (u_2)	4,139	12,417
Relative out (w_2)	2,279	6,837
Absolute in (v_2)	3,154	9,462

Table 5: The Triangle Velocity Data on the First Stage, with a *Guide Passage Gate Vane*

Velocity Direction	Line Length (cm)	Velocity m/sec
Tangential in (u_1)	4,703	14,109
Relative in (w_1)	2,529	7,587
Absolute in (v_1)	6,692	20,076
Tangential out (u_2)	4,703	14,109
Relative out (w_2)	2,529	7,587
Absolute in (v_2)	4,945	14,839

Table 6: The Triangle Velocity Data on the Second Stage, with a *Guide Passage Gate Vane* with rotation of 1348 rpm

Velocity Direction	Line Length (cm)	Velocity (m/sec)
Tangential in (u_1)	4,249	12,870
Relative in (w_1)	2,529	7,587
Absolute in (v_1)	4,945	14,835
Tangential out (u_2)	4,249	12,870
Relative out (w_2)	2,529	7,587
Absolute in (v_2)	3,123	9,39

DISCUSSIONS

Based on cross flow turbine test results without a Guide Passage Gate Vane the turbine rotation was 1215 rpm as shown in **table 1**. For the cross flow turbine test results with a guide passage gate vane, the turbine rotation was 1348 rpm, as shown in **table 2**.

The Triangle Velocity Analysis for a Cross Flow Turbine without a *Guide Passage Gate Vane.*

There are three triangle velocities which will be analyzed, namely: the tangential velocity, the relative velocity, and the absolute velocity. The tangential velocity is the first speed being analyzed. The tangential speed is about 12,717 m/sec (u_1), The Turbine Rotation (n) = 1215 rpm

The First Stage Triangle Velocity without a *Guide Passage Gate Vane.*

The depiction of the first stage triangle velocity without a ***Guide Passage Gate Vane*** with a scale of 1 cm = 3 m/sec as seen in figure 5, resulted a tangential velocity value, a relative velocity and an absolute velocity value asseen in Table 3**.**

The tangential velocity calculation result is described as the direction of the first tangential velocity. The tangential velocity direction is parallel to the outer diameter of the turbine runner. The second depiction is the relative velocity in the direction of the incoming flow of the turbine blade (w_1) and the third depiction is the absolute velocity direction in the nozzel line with a nozzle angle of 16^0. The relative velocity value and the absolute velocity value are measured at the intersection between the two velocities. The absolute velocity is the resultant between the tangential velocity direction and the relative velocity direction.

The First Stage Entrance Triangle Velocity Analysis

From the first stage triangle velocity it is found that the absolute velocity: v_1 = (18,096 m/sec), the tangential velocity (u_1) = 12,717 m/sec, the entry angle $\beta_1 = 46{,}84^0$, the first stage nozzle entrance angle $\alpha_1 = 16^\circ$; and the relative velocity (w_1) = (6.837 m /sec).

The First Stage Exit Triangle Velocity Analysis

The tangential velocity of the inner side of the runner, u_2 of the triangle tangential velocity on the inside of the first runner equals $u_1 = u_2$ = 12.717 m/sec. At the first exit portion, the relative velocity at the first stage exit is w2 = 6.837 m /sec, absolute speed v_2 = 14.439 m/sec, Output angle of first level pipe $\alpha_2 = 133.16\ ^\circ$.

First is calculating the turbine power from the first stage triangle velocity without a guide passage gate vane. Secondly, is calculating the additional turbine power from the second stage triangle velocity without a gate passage gate vane.

Turbine Power Calculation

From the triangle velocity results above, the turbine force and turbine power were, on the first stage were calculated. The water flow rate (Q) = 0,2874 m^3/sec, the water mass flow rate ṁ = 287,4 kg/sec, the turbine force (F) = 3654,87 N, the turbine brake horse power (BHP) = 46478,99.

The Second Stage Triangle Velocity Without a *Guide Passage Gate Vane*

The first stage triangle velocity depiction without a guide passage gate vane with a scale of 1 cm = 3 m/sec as seen in figure 6 resulting a tangential velocity value, a relative velocity and the absolute velocity value as seen in Table 4.

The First Stage Entrance- Triangle Velocity Analysis

From the triangle velocity, it was found an absolute velocity: v_1 = (14.439 m/sec), a tangential velocity (u_1) = 12.417 m/sec, an inlet angle $\beta 1 = 28{,}26^0$, a first stage nozzle entry angle $\alpha_1 = 16^0$ and a relative velocity (w_1) = (6,837 m/sec).

The First Stage Exit Triangle Velocity Analysis

From the turbine triangle velocity analysis, the runner inside tangential velocity, u_2, is equal to the runner inside tangential velocity on the first stage u_1. So that $u_1 = u_2 = 12.417$ m/sec.

At the first stage exit, the relative velocity w_2 = 6.837 m/sec, the absolute velocity v_2 = 9,462 m/sec and the nozzle first stage angle $\alpha_2 = 148{,}19\ ^o$

Furthermore, the turbine power produced was calculated based on the first stage triangle velocity without a gate vane guide passage and an additional power from the second stage without a guide passage gate vane .

Turbine Power Calculation

From the results above, then the triangle velocity and the turbine power were calculated. **Flow rate (**Q) = 0,2874 m^3/sec, mass flow rate **(**ṁ) = 287,4 kg/sec, turbine force (F) = 3568,64 N, second stage Brake Horse Power (BHP) **=** 44311,80 watt.

Thus, the power produced by the cross flow turbine without a guide passage gate vane is: Total power = 46478,99 watt (Power (BHP) first stage) + 44311,80 watt (Power (BHP) second stage) = 90790,79 watt

The Cross Flow Turbine Analysis with a *Guide Passage Gate Vane*.

There are three triangle velocity that will be analyzed, namely: the tangential velocity, the relative velocity and the absolute velocity. The tangential velocity is the first velocity to be analyzed. The tangential velocity value is 14,109 m/sec

The tangential speed value is 12,717 m/s (u_1), the turbine rotation (n) = 1215 rpm and the turbine rotation (n) = 1348 rpm.

The First Stage Triangle Velocity with a *Guide Passage Gate Vane.*

The first stage triangle velocity depiction with a ***guide passage gate vane*** with a scale of 1 cm = 3 m/sec seen in figure 7, resulted a tangential velocity value, a relative velocity and an absolute velocity value as seen in Table 5.

The tangential velocity calculation result is described as the direction of the first tangential velocity. The velocity direction is parallel to the outer diameter of the turbine runner. The second depiction is the relative velocity in the direction of the incoming flow of the turbine blade (w_1) and the third depiction is the absolute velocity direction in the nozzle line with a nozzle angle of 16°. The relative velocity, and absolute velocity value are measured at the intersection between the two velocities. The absolute velocity is the resultant between the tangential velocity direction and the relative velocity direction. The triangle velocity was captured using the Autodesk Inventor 2008 software.

The First Stage Entrance Triangle Velocity Analysis

From the triangle velocity all velocity components could be found. The absolute velocity on the first stage v_1 = (20.076 m/sec), the tangential velocity (u_1) = m/sec, the blade entry angle $\beta_1 = 46,84^0$, the first stage nozzle entry angle $\alpha_1 = 16^o$, and the relative velocity (w_1) = (7.587 m/sec)

The First Stage Exit Triangle Velocity Analysis

The tangential velocity on the runner inner side u_2 of triangle velocity acquisition obtains a tangential velocity on the inside of the first stage runner which is equal $u_1 = u_2$ = 14.109 m/sec. At the first stage exit, the relative velocity on the first stage exit is w_2 = 7.587 m/sec, the absolute velocity v_2 = 14.839 m/sec, the first stage nozzle angle α_2 = "133,16 º.

The turbine power generated was calculated from the first stage triangle velocity with a guide passage gate vane, and an additional power from the second stage with a guide passage gate vane.

Turbine Power Calculation

From the first stage triangle velocity result above, then turbine force and turbine power were calculated. The turbine water flow rate (Q) = 0,2874 m^3/sec, the water mass flow rate ($\dot{m}$) = 287,4 kg/sec, the turbine force (F) = 4054,92 N, and the brake horse power (BHP) = 57210,9.

The Second Stage Velocity Triangle with a *Guide Passage Gate Vane*.

The second stage triangle velocity using a guide passage gate vane with a scale of 1 cm = 3 m/sec as seen in figure 8, resulted a tangential velocity value, a relative velocity and the absolute velocity value as seen in table 6.

Analysis of First Stage Entrance Triangle Velocity

From the first stage triangle velocity, the absolute velocity v_1 = (14,835 m/sec), the tangential velocity (u_1) = 12,870 m/sec, the blade entry angle $\beta_1 = 30^0$, the first stage nozzle entry angle $\alpha_1 = 16^o$ and the relative velocity (w_1) = (7.587 m/sec)

Analysis of First Stage Exit Triangle Velocity

The tangential velocity on the inner side of the runner u_2 of the triangle velocity, tangential velocity on the inside of the first stage runner equals $u_1 = u_2$ = 12,417 m/sec. In the first stage exit, the relative velocity at the first stage exit is w_2 = 7.587 m/sec, absolute velocity v_2 = 9,39 m/sec, first stage "nozzle α_2 = "143.79 º. "

Furthermore, from the first stage with a guide passage gate vane triangle velocity, the power generated was calculated.

Turbine Power Calculation

From the first stage triangle velocity result above, the turbine force and turbine power were calculated. The water flow rate (Q) = 0,2874 m^3/sec, the water mass flow rate ($\dot{m}$) = 287,4 kg/sec, the turbine force (F) = 3698,84 N, and the turbine brake horse power (BHP) on the first stage = 47604,07 watt.

Thus, the power produced by the cross flow turbine with a guide passage gate vane is about 57210,9 watt (First stage BHP) + 47604,07 watt (Second stage BHP) = 104814,97 watt.

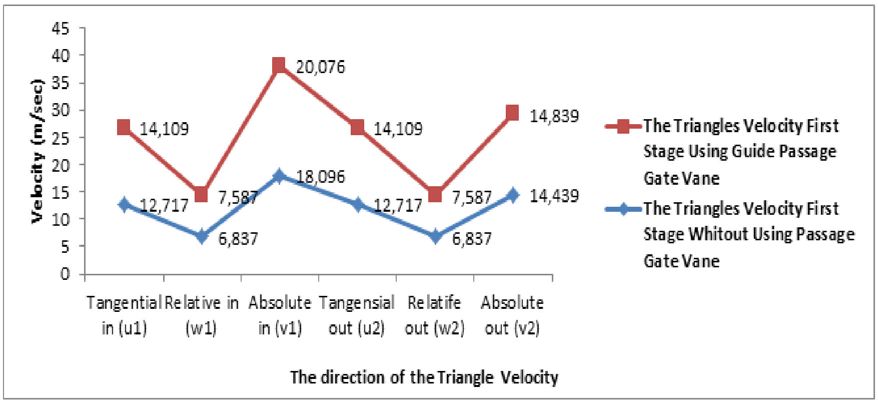


Figure 9: Tangential Velocity, Relative Velocity, Absolute Velocity First Stage.

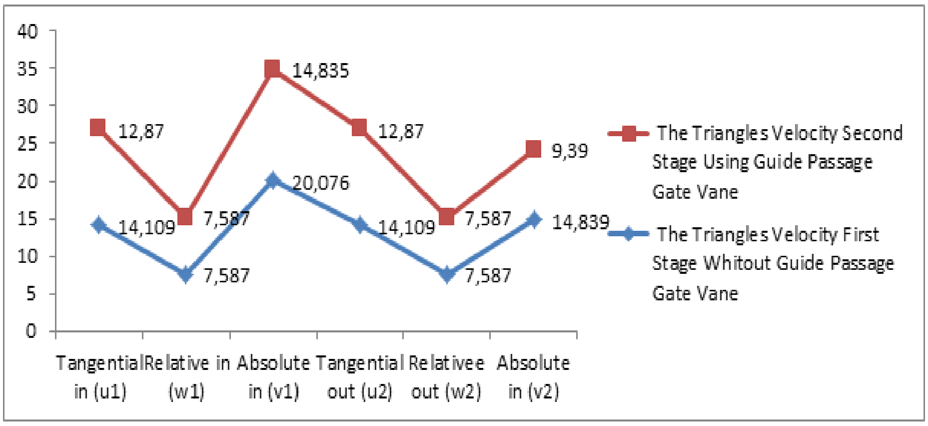


Figure 10: Tangential Velocity, Relative Velocity, Absolute Velocity Second Stage.

The tangential velocity, relative velocity, absolute velocity cross turbine with a guide passage gate vane at the first stage and second stage is higher than the gate vane cross turbine without a guide passage (figure 9, 10).

Table 7: Power Outputs Difference

Working Fluid	Total Output Power (watt)	Differences Power Output (watt)
Cross flow turbine without a guide passage gate vane	**90790, 79**	14024,18 (13,34 %)
Cross flow turbine with a guide passage gate vane	**104814,97**	

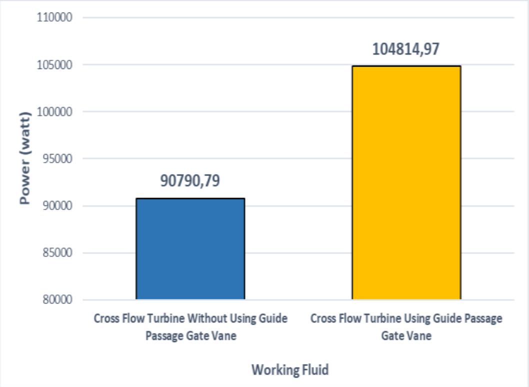


Figure 11: Output Power Analysis Working Cross Flow Turbine (with and without a Guide Passage Gate Vane).

Based on the triangle velocity method analysis, with a guide passage gate vane addition, it produced turbine power of 104814,97 watt, while without a guide passage gate vane, the turbine power is about 90790,79 watt. There was a power increase of 13.34% (table 7, figure 11)

CONCLUSIONS

The result of cross flow turbine performance analysis using the triangle velocity method is as follows:

- Based on the analysis of the cross flow turbine without a guide passage gate vane triangle velocity, the turbine power generation is as big as 90790, 79 watts (first stage power + second stage power = 46478,99 watt + 44311,80 watts).
- Based on the analysis of triangle velocity cross flow turbine with a guide passage gate vane, it generated power of 104814,97 watt (power first stage+ power second stage = 57210,9 watt + 47604,07 watt).
- With a guide passage gate vane addition attached on the cross flow turbine runner, there was an turbine power increase about 13.4%.

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APPENDIX

Triangle Velocity [7]

- Tangential Velocity (u)
- Relative Velocity (w)
- Absolute Velocity (v)

Tangential Velocity

Equition 1

$$v_{\tan gensial}(u) = \frac{\pi . d . n}{60}$$

Where :

d= diameter runner

n = Turbine Rotation

Mass flow rate ((ṁ) [8]

ṁ = Q x ρ Equition 2

where :

Q = flow rate (m^3/s)

ρ = density (kg/m^3)

Force tangensial (F_r)

F_r= ṁ. Δv equition 3

Where :

ṁ = mass flow rate

Δv = initial velocity- final velocity (m/det)

Brake Hourse Power (BHP)

BHP= F_r. Δv (watt) Equition 4

where :

F = gaya (N)

F = ṁ.Δv (N)

Δv = initial velocity- final velocity (m/det)