American Journal of Engineering Research (AJER)
e-ISSN : 2320-0847 p-ISSN : 2320-0936
Volume-03, Issue-11, pp-85-92
www.ajer.org

Research Paper Open Access

Simulation of the Effect of Bucket Tip Angle on Bucket Splitter of a Pelton Turbine

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ABSTRACT: *The flow interaction in the rotating bucket of a pelton turbine influences the system power output. This work therefore sets out to investigate the effect of bucket tip angle on the power delivered to the bucket splitter. Simulation program was developed using Matlab to simulate the relationship between bucket tip angle, energy coefficient, bucket exit angle, and hydraulic efficiency to obtain an expression of power delivered to the bucket splitter. Research shows that at 3° bucket tip angle, the power delivered to the bucket splitter was maximum and decreases as the tip angle increases.*

Keyword: *Pelton turbine, bucket splitter angle, bucket tip angle, energy coefficient, power.*

I. INTRODUCTION

The high demand for a clean source of energy continues to increase as indicated by the increase in distributed generation technologies and adoption of renewable energy resources. Climate change and global warming have made renewable energy the most appropriate and fitting means of answering all these changes in our environment. Micro-hydro power plant (MHPP) is considered as one of the most reliable renewable energy in the world **[1]**. It is also one of the earliest small scales renewable energy and is still an important source of energy today. MHPP is appropriate in most cases for individual users or groups who are independent of the electricity supply grid. A MHPP is generally a hydroelectric power installation that can produce up to 100 KW of power. It does not encounter the problem of population displacement and is not expensive as solar or wind energy **[2]**.

There are many of MHPP around the world, usually in developing countries as they can provide an economical source with continuous supply of electrical energy compared to other small scale renewable energy. MHPP usually built on mountainous areas where hydropower resources are available to provide electricity for remote or rural areas. Furthermore, MHPP is often isolated from electricity supply grid. Therefore, it requires control to maintain constant frequency and voltage output in order to directly sustain load demands. This work focuses on the influence of tip angle and pressure distribution on the bucket surface which account for the power output of a MHPP (pelton turbine). Pelton bucket tip angle determines the power delivered to the bucket splitter

II. WORKING EQUATIONS:

Considering the flow inside the Bucket (figure1), a theoretical approach was carried out to estimate the pressure amplitudes during the initial impact and the power delivered to the splitter angle, since no pressure sensor is mounted directly on the tip of the bucket.

A kinematic study is performed to determine the angle of attack which is the tip angle at the instant of impact and consequently to determine the relationship between the tip angle, exit angle, energy coefficient and hydraulic efficiency, to develop an expression of power delivered to the splitter angle.

The jet is assumed to be 2D, and a longitudinal cut along bucket J symmetry plane was considered. The jet is animated by the absolute velocity u, while the bucket tip J moves with the peripheral velocityu_b. The first contact between bucket J tip and jet upper generator occurs with relative velocity V_r. The angle of impact of the tip γ is determined.

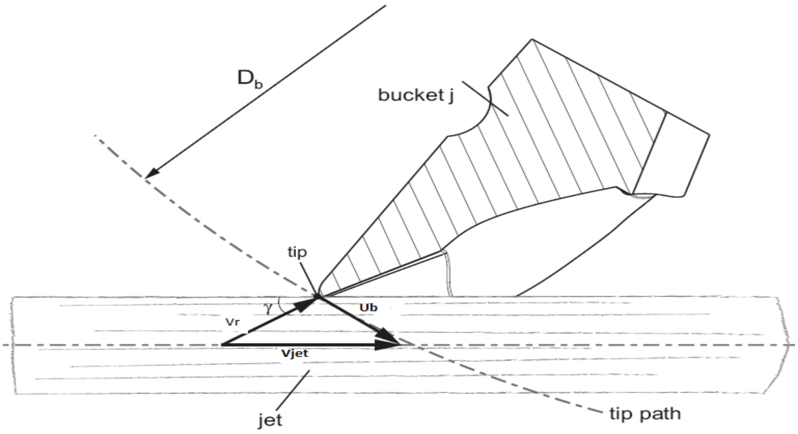


Fig. 1 2-D Velocity triangle at instant of impact

The position of bucket tip in a fixed frame of reference which origin coincides with the center of rotation of the runner is determined as follows:

$$\begin{cases} Xb\ (t) = \frac{D_b}{2}\ Cos\ (wt + wto) \\ Zb(t) = \frac{D_b}{2}\ Cos(wt + wto) \end{cases} \qquad [1]$$

wto is the arc between the datum and the first contact point.

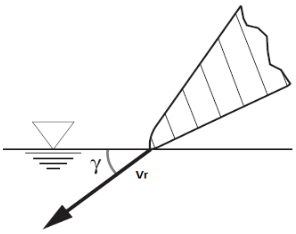


Fig. 2 Edge impact on the water surface

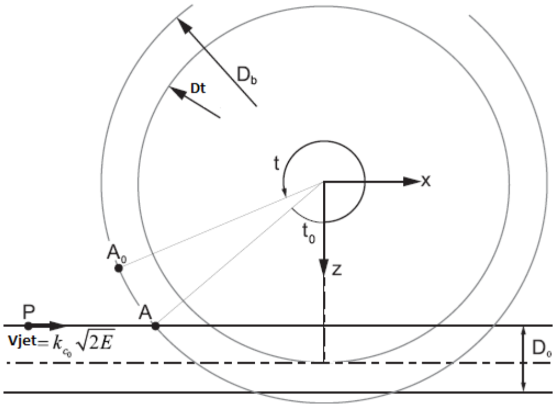


Fig.3 Kinetic path of the tip

$$wto = \text{arcos}\left(\frac{Dt - Dn}{Db}\right) \qquad [2]$$

The velocity of the bucket j tip is obtained by developing equation 1

$$\begin{cases} Uxb\ (t) = \frac{Dx_{b\,(t)}}{dt} = \frac{Db}{2}\sin(wt + wto)\,.\,\omega \\ Uzb(t) = \frac{Dz_{b\,(t)}}{dt} = -\frac{Db}{2}sin(wt + wto).\,\omega \end{cases} \quad \textbf{[3]} \qquad [3]$$

Consider the jet of diameter D_n oriented parallel to the x- axis. Let p be the water particle travelling on the jet upper generator at constant velocity $V_{jet} = k_{co}\,\text{x}\sqrt{2E}$ that is to encounter bucket j tip at position A. Particle p position is given by

$$\begin{cases} Xp\ (t) = k_{co}\,\text{x}\sqrt{2E\ x\ t} \\ Zp\ (t) = \frac{D_t - D_n}{2} \end{cases} \qquad [4]$$

And its velocity is

$$\begin{cases} Vxp\ (t) = \frac{d_{xp}\ (t)}{dt} = k_{co}\,\text{x}\sqrt{2E} \\ Vzp\ (t) = \frac{d_{zp}}{dt} = 0 \end{cases} \qquad [5]$$

The relative velocity component of particle p with respect to the bucket j tip is $V_r = V_{jet} - U$, at the instant of impact **[3].** Thus

$$\begin{cases} V_r xp\ (t) = k_{co}\,\text{x}\sqrt{2E}\ x\ \frac{Db}{2}\sin(wt + wto)\,.\,\omega \\ V_r zp\ = \frac{D_b}{2}\ Cos(wt + wto).\,\omega \end{cases} \qquad [6]$$

The relative angle of impact of the tip is expressed as

$$\gamma = \text{arc tan}\left(\frac{V_r zp}{V_r xp}\right) + \rho \qquad [7]$$

Where γ *is* the tip angle and ρ is the angle of setting of bucket j.

$$\rho = \text{arc sin}\left(\frac{2r}{D_b}\right) \qquad [8]$$

Introducing the energy coefficient $\varphi_1$the expression for the angle of attack γ is given by:

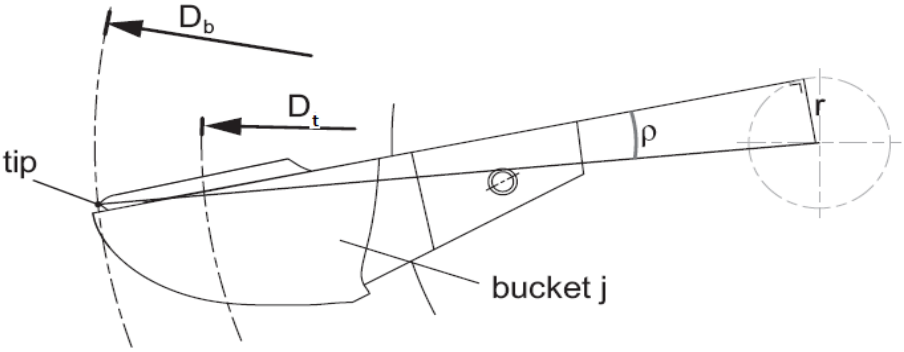


Fig. 4 Bucket angle of setting

$$arc\ cot\gamma = \left(\frac{D_t - D_n}{\varphi_1{}^{1/2} k_{co} - \frac{D_b}{D_t}\sqrt{1-(\frac{D_t-D_n}{D_b})^2}}\right) \ \textbf{[4]} \qquad [9]$$

The angle γ is a function of three parameters, $\gamma = \gamma(\varphi_1, D_n, k_{co})$.

From equation 9,

$$\varphi_1{}^{1/2} = \left(\frac{D_t - D_n}{cot\gamma\ k_{co} - \frac{D_b}{D_t}\sqrt{1-(\frac{D_t-D_n}{D_b})^2}}\right)$$

$$ie\ \varphi_1 = \left(\frac{D_t - D_n}{cot\gamma\ k_{co} - \frac{D_b}{D_t}\sqrt{1-(\frac{D_t-D_n}{D_b})^2}}\right)^2 \qquad [10]$$

The hydraulic efficiency η is by definition expressed as:

$$\eta = \frac{p_t}{p_h} = \frac{p_t}{\rho QE} \ \textbf{[5]} \qquad [11]$$

With substitutions equations 10 & 11 finally reduce to

$$\eta = 2(\frac{V_{jet}}{\sqrt{\varphi}} - \frac{1}{\sqrt{\varphi}}) \text{ x } (1 + (1 - \Delta) \text{ x } \cos\beta_2 \ \textbf{[5]}$$

$$\eta = \frac{p_{wheel}}{p_h} = \frac{p_{wheel}}{\rho gH} = 2(\frac{V_{jet}}{\sqrt{\varphi}} - \frac{1}{\sqrt{\varphi}}) \text{ x } (1 + (1 - \Delta) \text{ x } Cos\beta_2$$

$$P_{wheel} = 2\rho gH(\frac{V_{jet}}{\sqrt{\varphi}} - \frac{1}{\sqrt{\varphi}}) \text{ x } (1 + (1 - \Delta) \text{x } Cos\beta_2 \ \textbf{[6]} \qquad [12]$$

Equation 12 shows the relationship between tip angle, exit angle, hydraulic efficiency and energy coefficient to develop the power delivered to the splitter and the wheel by the fluid through the nozzle **[4-6]**.

2.1 Determination of Nozzle Velocity V_2jet

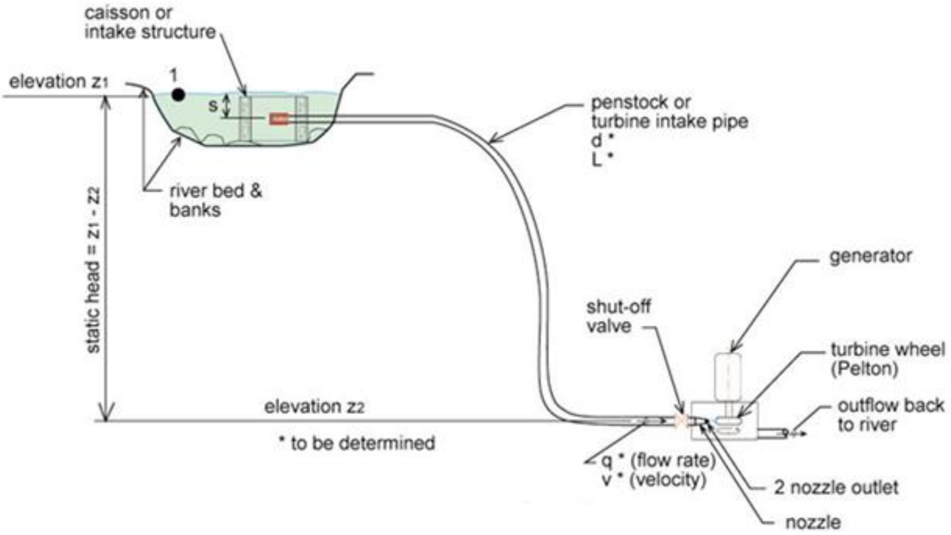


Fig. 5 Flow from the reservoir to the nozzle outlet

Water to drive a pelton wheel is supplied through a pipe from a river bed or lake as shown above, The maximum power output will be determined using the static head to check the influence of head on the power output of a pelton wheel and also the bucket shape runner or wheel. The head loss due to friction in the pipeline will be considered while minor losses neglected.

Calculations for hydro turbine jet impact velocity are based on the same sort of calculations done for pump systems, except there is no pump. The energy is provided by the difference in elevation between the inlet and outlet of the system, shown above .The inlet (point1) is defined as the surface elevation of the water source and the outlet is at the nozzle outlet (point2), the velocity v_1 is the velocity of fluid particle at the water source surface; velocity v_2 is the velocity of the water jet at the nozzle. The pressure head at point 1 and 2 is equal to zero. Applying the Bernoulli's equation to link the flow from the reservoir to the nozzle outlet, we have

$$Z_1 - Z_2 - H_f = \frac{V_2^{\,2}}{2g}$$

$$V_{jet}\ (\text{m/s}) = \sqrt{2 \, x \, g \, (Z_1(m) - Z_2(m) - H_f\,(m)}\quad \textbf{[7, 8]} \qquad [13]$$

2.2 Shaft Power Output $\dot{W}_{shaft}$:

The shaft output is not only influenced by the force generated on the bucket as the jet impinges on the bucket splitter angle causing the rotary motion of wheel thereby affecting the shaft power output and the torque on shaft but also the head which delivered energy through the nozzle to the bucket.

The torque to the shaft is

$T = F_{bucket}\, r_m$

$$\dot{w}\dot{W}_{shaft} = \rho\, Q\, U\, (U - V_{jet})\,(1 - \cos\beta_2) = 2\rho Q\,(U^2 - UV_{jet})\ \textbf{[9, 10]} \qquad [14]$$

Since $V_{jet} > U$, shaft work being done is negative since work is done on the system and torque is maximum when U = 0.

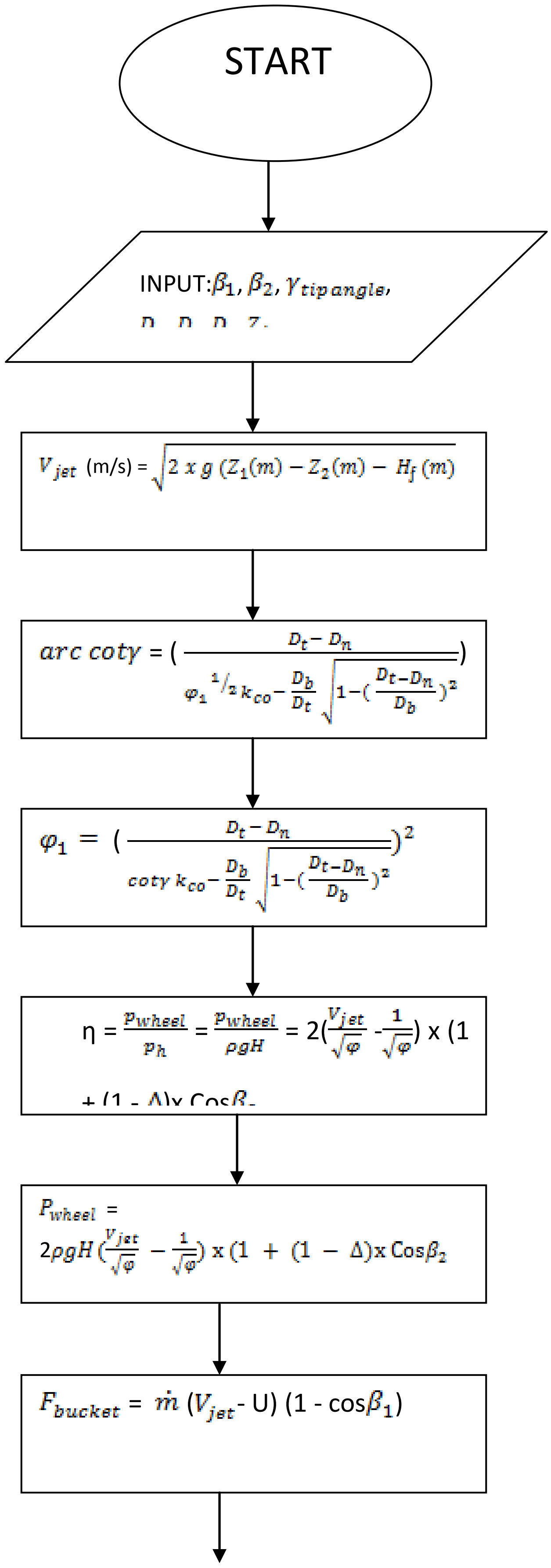
III. SIMULATION

Simulation was performed to investigate the effect of power delivered by the bucket Tip Angle to the bucket splitter which then generates a force on the bucket surface to drive or retards bucket motion.

3.1 Basic Equations

The simulation model equations used in estimating the power delivered by the bucket tip angle to the bucket splitter and also the pressure distributed on the bucket surface in the study were derived from section 2.0

3.2 Simulation Flow Chart



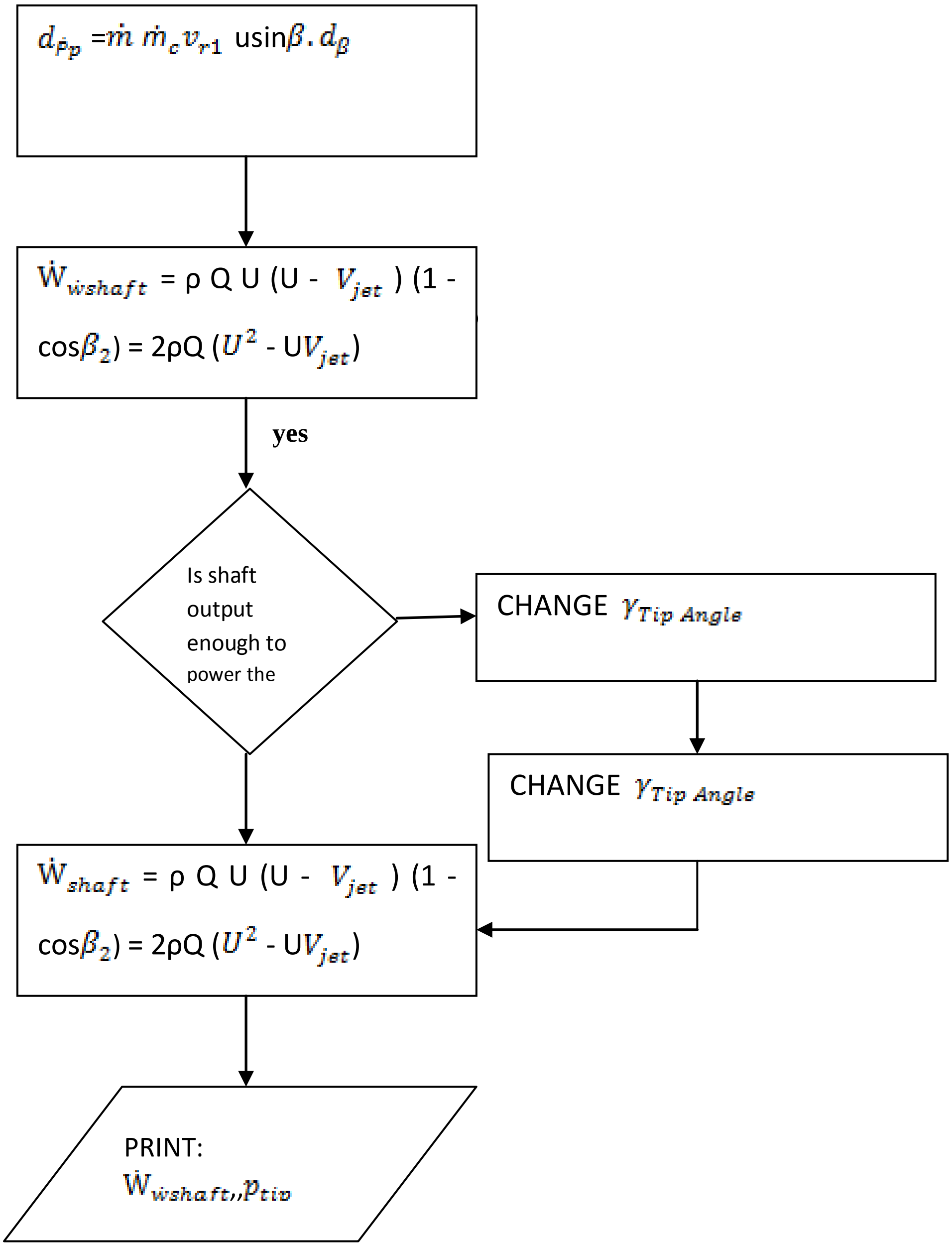


Fig 6: Simulation program flow chart

3.3 Results and Discussions

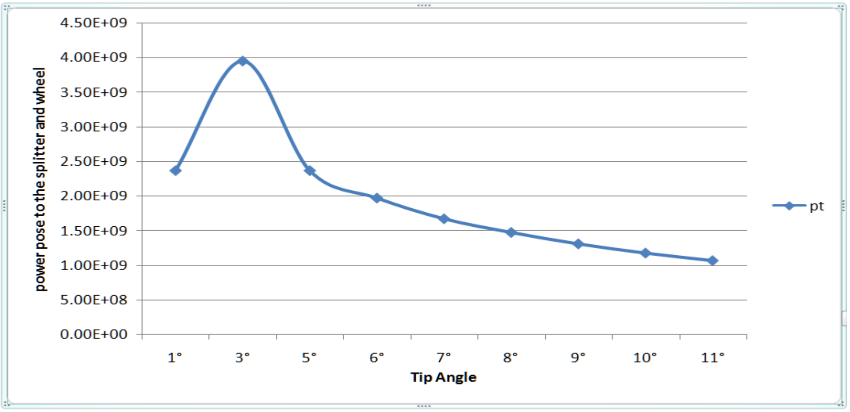


Fig.7: Relationship between the power delivered to the splitter angle and bucket tip angle

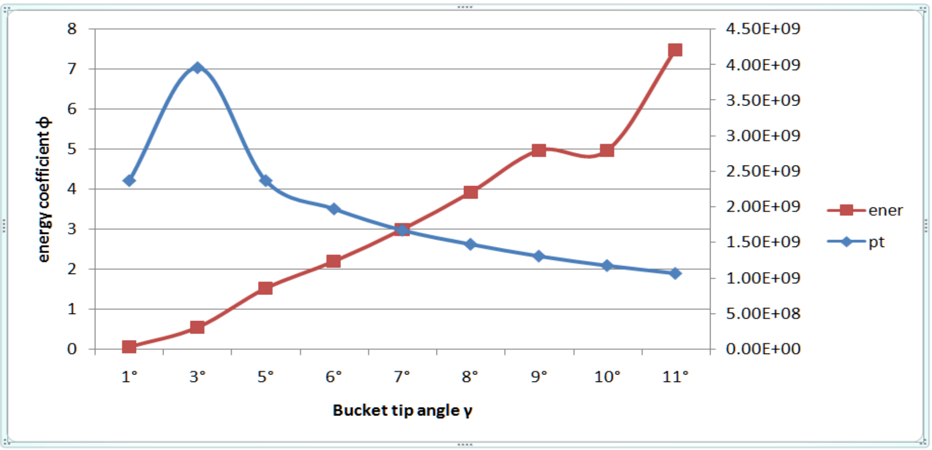


Fig. 8: Relationship between the bucket tip angle, energy coefficient and power directed to the splitter and the wheel using simulation to predict our results.

The results of our study show that power delivered to the bucket splitter and the wheel due to the bucket tip angle increases from 1^o and got the peak at 3° where power output values were (2.3677 x 10^{09} kW and 3.9526 x 10^{09} kW respectively) and that there was a continuous decrease in the power delivered to the splitter as the tip angle increases from 5° to 11°, that is 2.3677 x 10^{09} kW to 1.0657 x 10^{09} kW. The energy coefficient was minimum at 1° with a slightly increase at 3°tip angle after which it increases continuously to maximum at 11° tip angle.

IV. CONCLUSION

The results of our study show that power delivered to the bucket splitter and the wheel due to the bucket tip angle was greater at 3° where power output was 3.9526 x 10^{09} kW showing that the pelton bucket with hemispherical cup shape should be designed with a tip angle of 3° to deliver a better power output on the system

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