DEVELOPMENT OF AN IMPULSE TURBINE HYDROPOWER PLANT TRAINING SYSTEM

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Abstract

Hydropower plant complex structure offers challenges to college students in efficiently understanding the working principles of hydropower plants. To overcome these complexities, a hydropower plant model with an impulse turbine was built to deepen students understanding of working principle of hydropower plants using locally sourced materials. Two experiments were conducted with the model, simulating two scenarios: when the valve is half-opened and when the valve is fully opened. To analyze the data derived from the experiments, a Python code was developed to interface with the primary data. The program produced secondary data that includes turbine effective head, flowrate, water pressure, and turbine output power. The study examined the relationship between the turbine effective head with the other parameters. The finding showed that the generator output power and water pressure grow with the turbine effective heads for the two cases in general. However, the growth of these parameters was higher for the half-opened case compared to the fully-opened case, except for the water flowrates and turbine shaft speed. The model proved to be a promising tool for conducting experiments concerning hydropower plants, which can help reinforce the theoretical knowledge gained in the classroom.

Keywords: *Hydropower plant, Impulse turbine, Experiments, Model, Effective head, College students*

Introduction

Energy remains one vital quantity whose needs keep growing exponentially, which is characterized by an increasing population and our need to keep advancing our daily lives' activities. Consequently, global energy consumption is predicted to rise by 50% in 2050, as reported by the U.S. Energy Information Administration and cited by (Cergibozan, 2022). Furthermore, the socio-economic progress of a nation is tied to energy availability, especially electrical power. For example, in Nigeria, the dwindling power availability has caused the economy an annual loss estimated at about US$26.2 billion, which translated to around 2% of the nation's growth in domestic product (Sani & Scholz, 2022). The need for power availability is therefore key to a nation's development. However, a major part of the energy needs of the globe are met by fossil fuels; about 80.1% of the global energy needs are supplied by fossil fuels (Umar et al., 2022). And the use of fossil fuels comes with associated challenges such as unpredictable costs, global warming, and depleting reserves (Abbasi et al., 2022, Dolah et al., 2022).

Alternative means of energy, such as solar, wind, biofuels, hydrothermal, hydropower, etc., have gained huge attention globally and have sustained rapid penetration to help curb the negative effects associated with the use of fossil fuels. In the year 2020, renewable energy was responsible for 29% of global electricity production (Yuguda et al., 2022). Among various renewable energy sources, hydropower accounts for over 54% of alternative energy production capacity globally, representing the highest share of the accumulated sum of installed renewable energy capacity worldwide (Yuguda et al., 2022). In Nigeria, the projected active installed potential power of hydropower plants stands at 12,220 MW (Yuguda et al., 2022). Hydropower has great benefits, such as cheap means of electricity, a sustainable energy source, job opportunities, etc. Meanwhile, hydropower generating plants are complex structures.

Hydropower plants generate electricity via the conversion of water potential to mechanical energy on the turbine shaft. It is made up of various components such as the dam, forebay, intake, penstock, wicket-gate, turbine runner, turbine shaft, generator shaft, generator, power house, draft tube, tailrace, etc., as can be seen in figure 1 (Sadanandam, 2023).

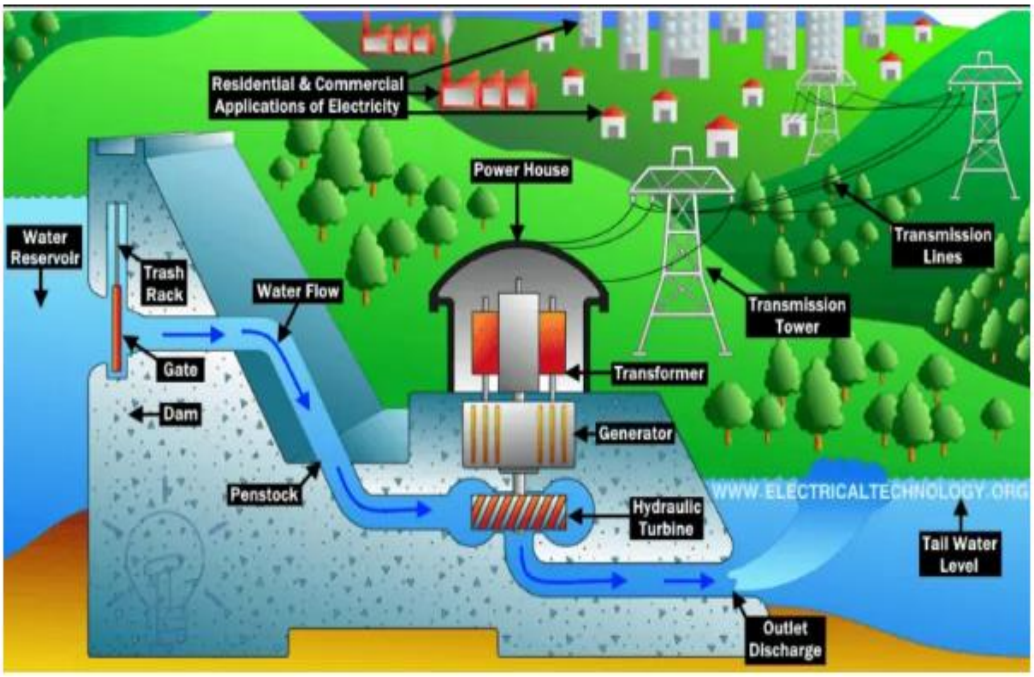

Figure 1: Layout and components of hydropower plant (Technology, 2023)

They can be classified based on the types of turbines, water flow, and head, as depicted in figures 2 and 3, for example. In general, the structure of hydropower plants is very intricate.

Due to the complexity of hydropower plants, college students in Nigeria, during industrial visitations to hydropower plant installations, do find it difficult to connect what is taught in the class regarding hydropower plants with what they are exposed to during these trips; in the power house of the hydropower plants, they are mostly restricted to the generator floor. During these visits, the plants are usually pressurized, and access to most details is limited. As such, students tend to swim with limited knowledge of hydropower's working principles. This paper is oriented to bridge this gap via the intentional modeling of a hydropower plant that can be deployed for experimental purposes in college laboratories. Consequently, the primary data derived from the experiments are interfaced with a computer program developed in Python to help in the computation and analysis of the secondary data such as turbine effective heads, water flowrates, water pressure, and generator output power, which are germane to the performance of the hydropower plant model.

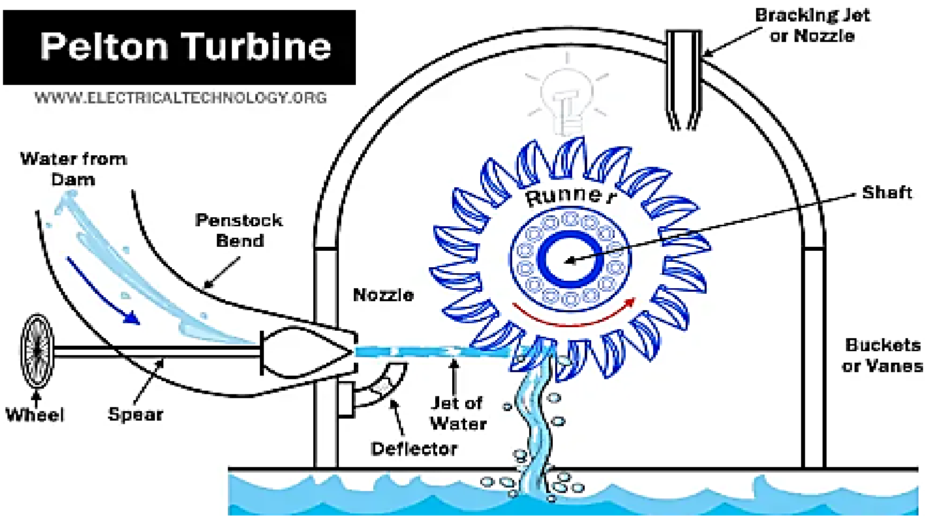

Fig. 2: Impulse turbine (Technology, 2023)

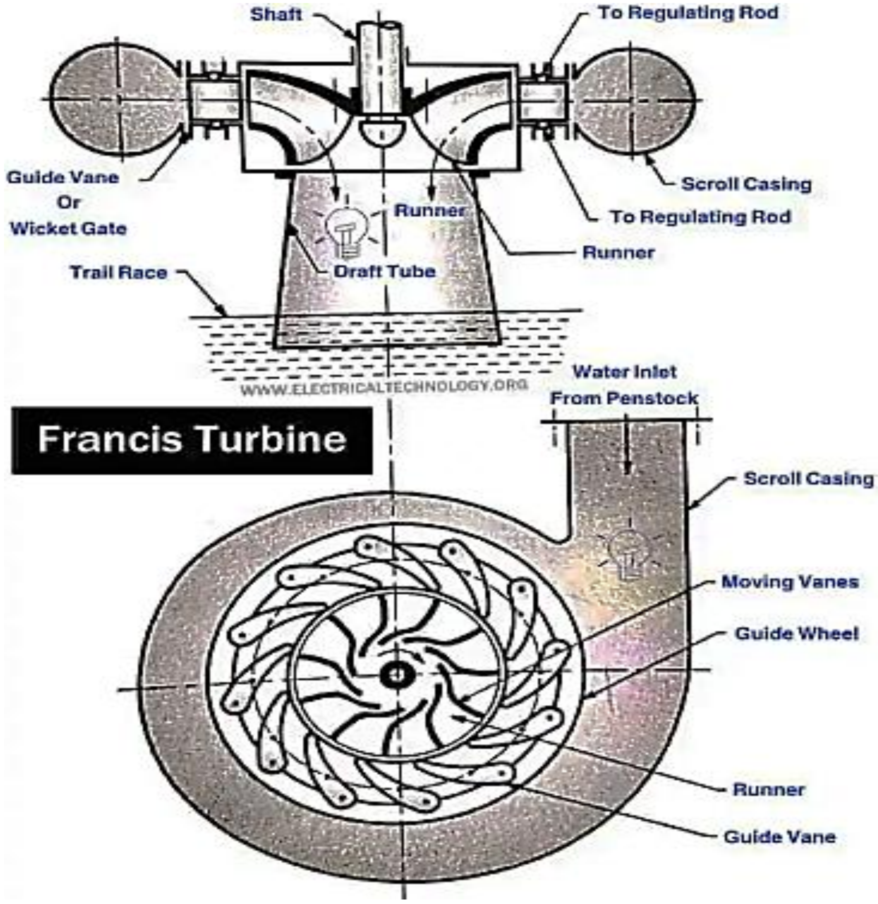

Fig. 3: Reaction turbine (Technology, 2023)

Methodology

Materials

This paper chose to go with locally available materials. The materials used for the modeling of the hydropower plant are presented in Table 1.

Table 1: The list of materials used for this study

SN	Materials	Purpose
1	Transparent glass sheet	Used as a shield for the turbine
2	Tin-can	Used as the turbine hub
3	12 liters rubber bucket	Used as the reservoir
4	PVC pipe	Used for the penstock
5	Rubber spoon	Served as the turbine runner
6	Radio antenna	Used as the turbine shaft
7	Valve fitting	used as the governor control of water flow and as the nozzle
8	Plywood	used as the foundation for the power house
9	12 volt dynamo	used as the generator
10	Car fuel pump	Used for recirculation of water from the tail race to the reservoir to maintain a require head.
11	Tachometer	Used for measuring turbine shaft speed

Furthermore, Fig. 4 shows the hydropower plant model components for this study.

Fig. 4: (a) Penstock (b) Reservoir (c) Turbine runner (d) Water circulation pump (e) and (f) Flow control valve

Method

An impulse turbine was the model in this study; the choice of this was to maintain constant pressure in the runner and for model simplification. The turbine blade was designed by dissecting the circumference of the tin-can at an angle of 45^0 into eight (8) equal parts. Holes were created at these spots to allow the insertion of the rubber spoons that serve as the turbine buckets. In the middle, where the rubber spoon meets to give the center point of the runner, the turbine shaft was installed with the help of cyanoacrylate glue. Furthermore, the penstock was oriented at an angle of 90^0 to the turbine bucket. Also, the transparent glass that serves as the turbine shield to prevent water loss from the system was dimensioned into 40cm × 60cm and held together using cyanoacrylate glue. Two pulleys were connected together by a thin belt at a centre distance of 45cm apart and were used to transfer the power from the turbine runner to the generator shaft; the turbine shaft and the generator shafts were firmly aligned to prevent vibration. The structure for the hydro turbine model was constructed using flat bars with the height between the turbine runner and the control valve maintained at a distance of 45cm each. Using the above-described methodology, Fig. 5 represents the hydro turbine model that was developed.

Fig. 5: Hydropower turbine model constructed at Federal Polytechnic Idah, Nigeria

For the purpose of appreciating how hydro turbines work and to aid experiments in colleges' laboratories, experiments were conducted using the developed hydropower turbine models. Quantities such as turbine effective heights, h_{eff}, water flowrates, Q, the pressure of water at various turbine effective height, $P_{h_{eff}}$, turbine shaft speed (ω_{shaft} in revolutions per minute), and the corresponding power that is generated were computed.

The reservoir in this study was assumed to be cylindrical in shape, and the turbine effective heights at various calibrated volumes of the cylinder (reservoir) were modeled using the equation for the volume of the cylinder (V_{res}) plus the distance of the turbine runner to the outlet of the water from the control valve as described by equation 1.

$$h_{eff} = \frac{V_{res}}{\pi r^2} + h_r \qquad (1)$$

Where r is the radius of the cylinder in (m^2) and a uniform diameter of $0.24m$ was assumed, h_{eff} is the turbine effective height (m), and h_r is the distance between the turbine runner and the control valve, which is a constant value of $45cm$.

Also, the flowrate at various turbine effective heights was determined via equation 2.

$$Q(m^3/s) = \frac{Volume\ of\ water\ (V_{res})\ at\ a\ given\ effective\ height}{Time\ taken\ for\ the\ volume\ to\ be\ completely\ discharged\ from\ the\ cylinder\ (t)} \quad (2)$$

The hydrostatic pressure relation as shown in equation 3 was utilized to obtain the pressure at the given turbine effective height.

$$P_{h_{eff}} = \rho g h_{eff} \quad (3)$$

Where ρ is the density of water (taken as $1{,}000 kg/m^3 at\ 4^0 C\ and\ 1\ atm$), g is the acceleration due to gravity taken as $9.8\ m/s^2$.

The output power of the hydro turbine model at various effective heads was modeled using equation 4 (Ugwu et al., 2022).

$$P_{out} = \rho g Q h_{eff} \eta \quad (4)$$

Where Q is the water flowrate at the corresponding turbine effective heads, and η is the combined efficiency of turbine components such as the turbine, generator, etc., which was assumed to be 70% in this study.

The experiments were conducted for eleven (11) different reservoir volumes (i.e., $0.002m^3$,$0.003m^3$, $0.004m^3$, $0.005m^3$, $0.006m^3$, $0.007m^3$, $0.008m^3$, $0.009m^3$, $0.0010\,m^3$, $0.0011\,m^3$, and $0.0012\,m^3$) at two conditions of the control valve (i.e., half-open and fully-open), and the important paramaters (turbine effective heads, water pressures, flowrates, and output powers) were computed using a developed computer code written in Python, and the results obtained are presented in Tables 2 and 3, respectively. Furthermore, the flowchart in Fig. 6 shows the algorithm developed for the code that was used for the computation of the turbine's essential parameters.

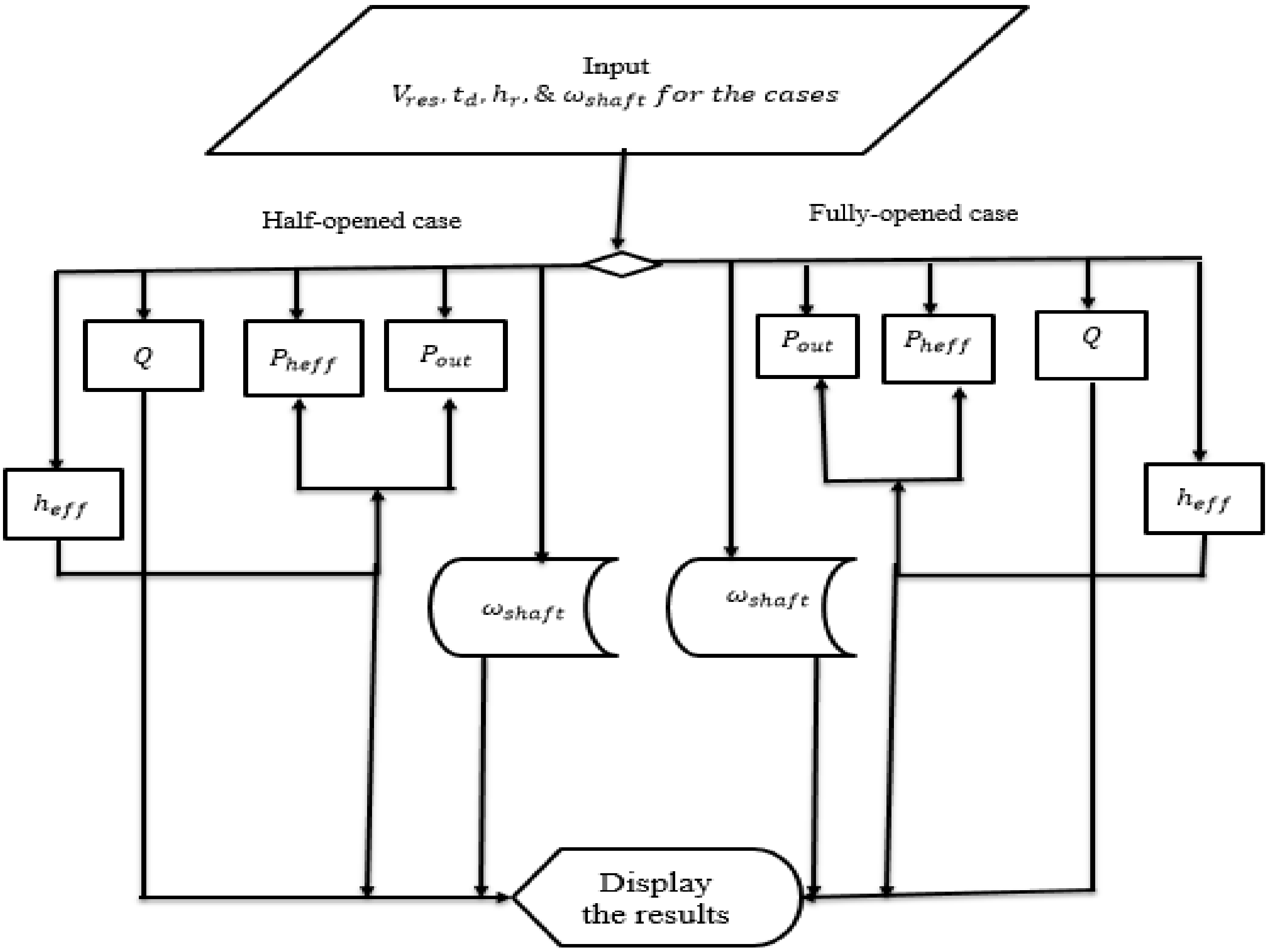

Fig. 6: Flowchart of the computer code used for the computation of the essential turbine parameters using experimental data from the hydropower plant model.

Results

The results of the experiments carried out using the developed hydropower plant model are reported in Tables 2 and 3:

Table 2: The results of the experiments conducted using the hydropower plant model for the half-opened condition of the control valve.

No of Trials	Reservoir volume ($V_{res}(m^3)$)	Time taken for discharge (t (s))	Corresponding effective turbine heights (h_{eff} (m))	Pressure at the corresponding effective height (P_{heff} (N/m^2))	Water flowrate (Q (m/s^2))	Turbine output power (P_{out}(kW))	Turbine shaft speed ($\omega_{shaft} rev/m$)
1	0.002	265	0.4942	4848.1020	0.0075	25.4525	48.6500
2	0.003	397.5	0.5163	5064.9030	0.0075	26.5907	68.9333
3	0.004	530	0.5384	5281.7040	0.0075	27.7289	55.7500
4	0.005	662.5	0.5605	5498.5050	0.0075	28.8671	56.800
5	0.006	795	0.5826	5715.3060	0.0075	30.0053	58.0000

6	0.007	927.5	0.6047	5932.1070	0.0075	31.1435	78.1333
7	0.008	1060	0.6268	6148.9080	0.0075	32.2817	59.1000
8	0.009	1192.5	0.6489	6365.7090	0.0075	33.4199	59.6000
9	0.0010	1325	0.6710	6582.5100	0.0075	34.5581	60.6000
10	0.0011	1457.5	0.6931	6799.3110	0.0075	35.6963	60.6000
11	0.0012	1591.5	0.7152	7016.1119	0.0075	36.8345	61.1000

Table 3: The results of the experiments conducted using the hydro turbine model for the fully-opened condition of the control valve

No of Trials	**Reservoir volume ($V_{res}(m^3)$)**	**Time taken for discharge ($t\ (s)$)**	**Corresponding effective turbine heights ($h_{eff}\ (m)$)**	**Pressure at the corresponding effective height ($P_{heff}\ (N/m^2)$)**	**Water flowrate ($Q\ (m/s^2)$)**	**Turbine output power (P_{out}(kW))**	**Turbine shaft speed ($\omega_{shaft} rev/m$)**
1	0.002	530	0.4942	4848.1020	0.0037	12.5565	97.3000
2	0.003	795	0.5163	5064.9030	0.0037	13.1180	103.4000
3	0.004	1060	0.5384	5281.7040	0.0037	13.6796	111.5000
4	0.005	1325	0.5605	5498.5050	0.0037	14.2411	113.6000
5	0.006	1590	0.5826	5715.3060	0.0037	14.8026	116.0000
6	0.007	1855	0.6047	5932.1070	0.0037	15.3641	117.2000
7	0.008	2120	0.6268	6148.9080	0.0037	15.9256	118.2000
8	0.009	2385	0.6489	6365.7090	0.0037	16.4871	119.2000
9	0.0010	2650	0.6710	6582.5100	0.0037	17.0487	120.4000
10	0.0011	2915	0.6931	6799.3110	0.0037	17.6102	121.2000
11	0.0012	3183	0.7152	7016.1119	0.0037	18.1717	122.2000

The behavior of key parameters with changes in turbine effective head are reported in Fig. 7.

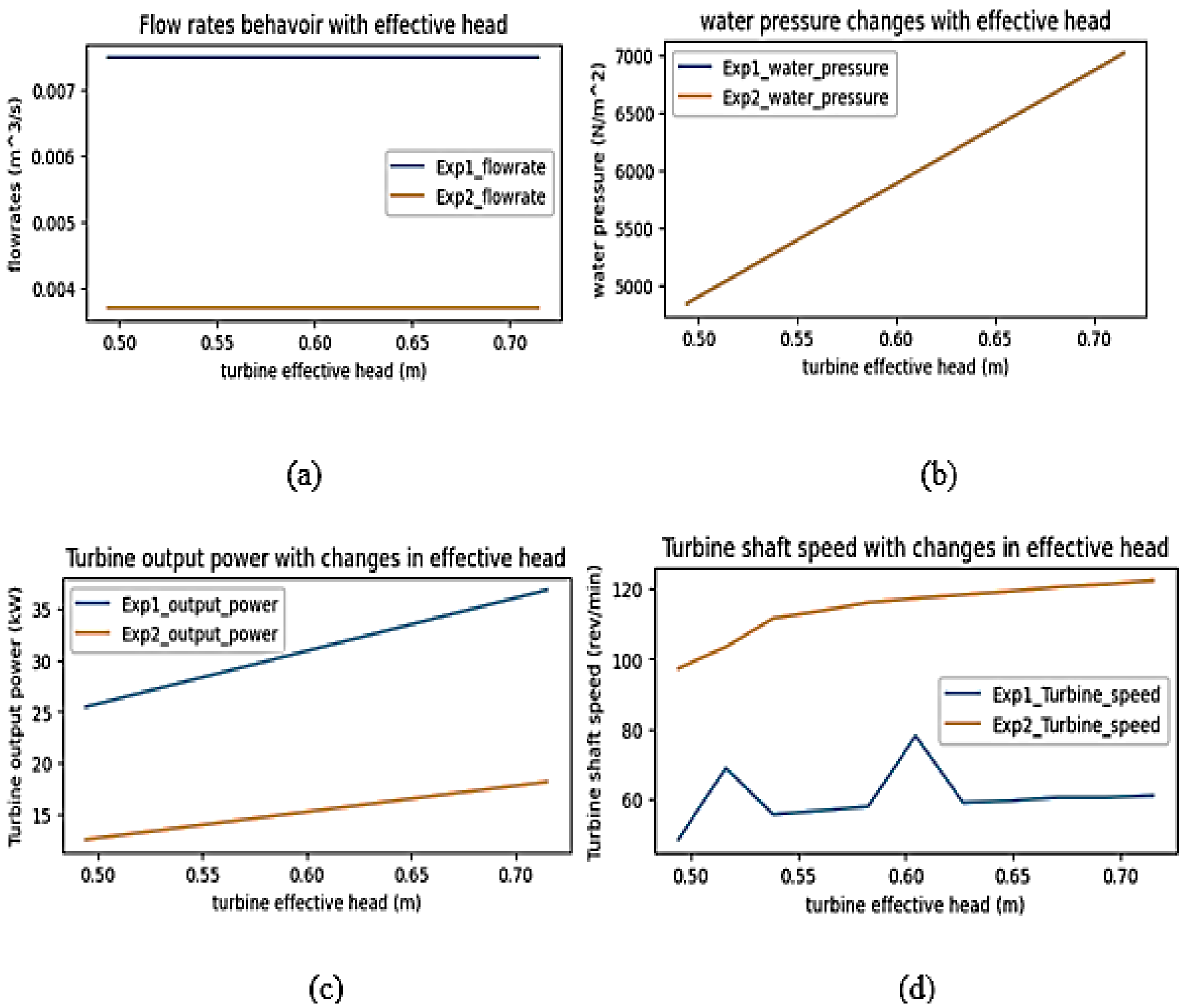

Fig. 7: (a) Variation of flowrates with turbine effective head, (b) Water pressure variation with turbine effective head, (c) Changes of turbine output power with the effective head, and (d) Turbine shaft speed changes with effective head, for both experiment 1 (half-opened) and 2 (fully-opened), respectively.

Discussion

In Tables 2 and 3, primary data, which are reservoir volume, time taken for discharge, and turbine shaft speed, were fed into the Python code and used to generate the important parameters, which are turbine effective heads, water pressures, flowrates, and output powers. The correlation among the data is then presented in Fig. 7 and discussed in the following subsections.

Flowrates behavior with changes in turbine effective head

In Fig. 7(a), it can be seen that the flowrates computed for that of experiment 1 (half-opened valve) are higher than those computed for experiment 2 (fully-opened valve) by around 50%. Also, in both conditions of experiments 1 and 2, the flowrates remain the same as the turbine effective head increases. In theory, the flowrate should grow with an increase in the turbine's effective head (Girma Misrak and Dribssa Edessa, 2014). However, this behavior may not be too far from the fact that the size of the reservoir considered in this study is not big enough to allow for that growth in flowrates to be obvious. As can be seen from the work of (Girma Misrak and Dribssa Edessa, 2014), where the growth of flowrates begins from a turbine head of about 2m as compared to 0.4942m in this study. Meanwhile, the performance of an impulse turbine depends more on the turbine's effective head than the flowrates.

The changes of water pressure with turbine effective head

For both experimental cases considered in this study, the water pressures remain the same. This is expected because for both experiments, the water volumes considered were the same, and as described by equation 3, the pressure has a linear relationship with the turbine head. So, as the turbine's effective head increases, the pressure of water also increases (First, 2015).

The output power derived with respect to turbine effective head

The performance of hydro power turbine is largely measured by the amount of electrical power that can be derived from it. During experiment 1, as can be observed with Fig.7 (c), it was found that the power output is greater as compared to that derived from experiment 2. This relationship is due to the higher flowrates registered during experiment 1 compared with the flowrates obtained during experiment 2. Furthermore, it can be observed that for both cases of the experiments, the output power is seen increasing, which can be due to the increase in turbine effective head and water pressure.

Turbine shaft speed behavior with turbine effective head

With increase of the turbine effective heads, the shaft speed is expected to increase. In this study, tachometer was used to pick the shaft speed and as shown in Fig. 7 (d), in experiment 1, the shaft speed was observed to increase linearly for the first few turbine head of about 0.52m, after which deviation started, where it remains fairly constant, and this was maintained to about 0.55m turbine head, and thereafter, the turbine speed increases steadily and asymptotically approach a speed of 120 rpm. In the case of experiment 2, the turbine speed is observed oscillating as the turbine effective head increases. And the grow of the turbine speed is not significant except for turbine head of 0.55m and 0.60m where the highest speed of approximately 70 rpm and 80 rpm, respectively were registered. Furthermore, as shown by Fig. 7 (d), the increase of shaft speeds observed for experiment 1 are greater than those observed in experiment 2. This behaviour can be due to the flowrates discrepancies observed for experiment 1 as compared to experiment 2.

Conclusion

The availability of energy to national building cannot be eschewed in any form and the need to get it available in cheap form and reduced pollution is of utmost importance. Common renewable energy resources are solar, wind, biomass, and hydro. Hydro contributed about 54% of alternative energy to the global energy capacity. Meanwhile, hydropower plants are characterized by complex structure which made it difficult to link comprehensively the knowledge gained in classroom by college students regarding hydropower plants and what the reality is. This study developed a hydropower plant model to assist in bridging this gap. For ease of reverse engineering, locally source materials were sourced for and were used for the construction of this model. The capacity of the reservoir is 12liters and reservoir was assumed as having a cylindrical configuration. The model was constructed and two experiments were performed for when the control valve is half-opened and fully-opened. Computer code written in Python was used to compute the essential parameters and used for analyzes. The model showed a promising route for conducting experiments regarding hydropower plants which can help in reinforcing the theoretical knowledge gained in classroom.

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