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Research Paper

Experimental Investigation on the Performance Analysis of a Constructed Hydro-Powered Coil Pump

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A hydro-powered water pumping system is one of the most important systems for upland areas in terms of supplying water for irrigation and daily usage. This paper presents the development and performance analysis of a hydro-powered coil pump, a clean energy pump that discharges and lifts water to a certain height without using any external energy sources. In this work, a coil pump with a radius of 0.152 m, 12 blades, four inlets, and two different outlets with 1″ and 3/8″ delivery pipes have been used for analyzing the performance of the pump separately. An open channel has been constructed with a length of 1.152 m, a width of 0.3028 m, and a depth of 0.254 m, incorporating a rectangular and v-notch. From the analysis, it has been seen that the coil pump with a v-notch and a 1″ delivery pipe shows better results in terms of discharge, power acquired, and water velocity through the open channel than the coil pump with a 3/8″ delivery pipe. However, for pumping water at the maximum manometric height, a 3/8″ delivery pipe with a rectangular notch performs better than the v-notch.

Keywords: renewable energy; coil pump; open channel; irrigation.

Notations

- A – area of the notch,
- B – width of the notches,
- C_d – coefficient of discharge,
- DP – delivery pipe,
- H – height of the water level from the base of the notches,
- Q_t – water discharge,
- V – water velocity,
- θ – angle of the v-notch.

1. Introduction

The availability of renewable energy (RE) in nature is a blessing for humans, as most RE sources are clean, environmentally friendly, and, most importantly, cost-free with substantial energy potential. According to the International Renewable Energy Agency (IRENA), in 2020, almost 7 461 218 GWh of electricity was generated from different RE sources, including 4 275 374 GWh from hydropower (58.4%), 1 484 585 GWh from onshore wind energy, 829 252 GWh from solar photovoltaic, and so on [1], as shown in Fig. 1a. On the other hand, the International Energy Agency (IEA) identifies hydropower as the largest source of energy (29%) along with coal (28%) and gas (27%) in terms of the global energy system flexibility for the year 2020 [2], as shown in Fig. 1b.

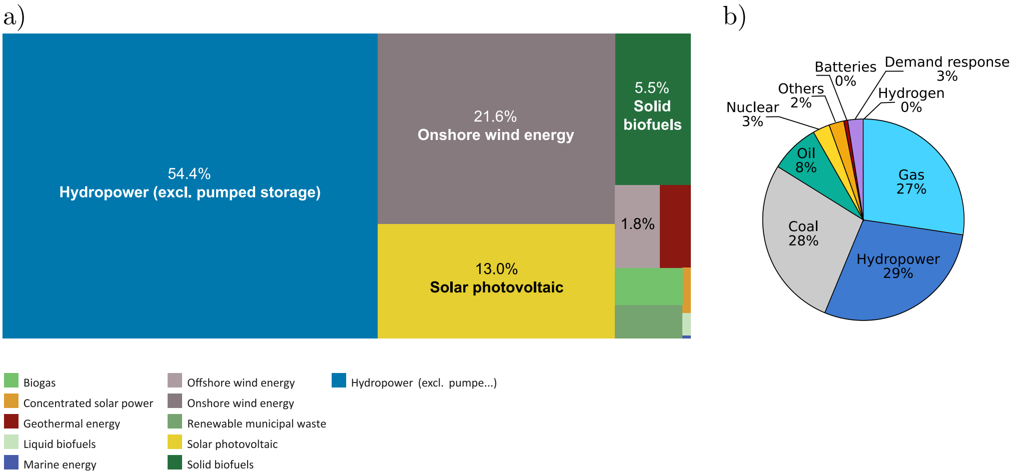

FIG. 1. Electricity generation worldwide in 2020: a) utilizing renewable sources of energy [1], b) global electricity system flexibility by sources [2].

A report on the hydropower market was published in 2021 by the IEA. In that report, global electricity supplied by hydropower accounted for one-sixth of the total electricity generation, and this contribution surpassed other renewable energy sources such as solar photovoltaics (PV), wind, geothermal, and bioenergy, and was nearly 55% higher than that of nuclear energy. The report also highlighted that the total capacity of hydropower has increased by about 70% over the last two decades. Furthermore, there is a goal to add 230 GWh, equivalent to 17%, of hydropower, between 2021 and 2030 [2].

Pumping water using various RE sources is more environmentally friendly, clean, and less expensive compared to conventional systems. GOPAL *et al.* [3] mentioned some of the combined RE systems, such as solar photovoltaic water pumping systems, wind energy water pumping systems, solar thermal water pumping systems, biomass water pumping systems, and hybrid renewable energy water pumping systems. According to INTRIAGO ZAMBRANO *et al.* [4], around 800 scientific and non-scientific papers were published until 2018 to describe procedures, designs, advantages, implementations, safety, and more for hydropower pumping systems. The authors also indicated that about 30 technologies of pressure-based hydro-powered pumping systems were classified worldwide. Some works of researchers, scientists, technologists, engineers, and students are mentioned below.

Using the hydraulic simulator EPANET, García Morillo *et al.* [5] investigated water demand scenarios in the Bembézar Margen Izquierda (BMI) irrigation district in southern Spain for the agri-food sector. From the simulated result, they found that a maximum of 270.5 MWh of power can be recovered, accompanied by a reduction of carbon dioxide emissions of around 108 tons.

Long ago, farmers regarded a spiral hydroponic pump a gift from God. But tremendous dedication, patience, time, and labor were invested by the researchers to unlock its benefits.

To validate the laboratory-based spiral pump, Naegel [6] tested different spiral pumps in the field at Bangued, in the Province of Abra, Philippines, to make it acceptable among the farmers. The performance test demonstrated that different parameters closely resembled the characteristics of laboratory-based spiral pumps. Conversely, Modi and Nourbaksh [7] experimentally investigated the helical coil pump for farm irrigation using wind energy to replace the available conventional commercial pump. Their experimental results suggested that helical coil pumps have a wide variety of applications, ranging from water pumping to firefighting and the transportation of chemicals. A coil pump, as a self-supporting arrangement, was investigated by Kassab *et al.* [8] in terms of wheel speed, number of coils, and submerged ratio. Their experimental results showed that the pump head is increased by increasing the number of coils without affecting the discharge. It was also proclaimed that by increasing the submerged ratio and wheel speed, the discharge also increased to the maximum state and then decreased. In another work by the same authors [9], the design of winding the hose pipe in the wheel, position, and diameter of the pipe and wheel were studied. The results showed better performance for three-layer coil pumps compared to single- and two-layer pumps. Additionally, in the case of multi-layer pumps, improved performance was observed when the pump inlet was placed at the top end.

Quiroga *et al.* [10] designed and implemented a hydro-powered water pump in an isolated community in Colombia. The community operated without any fuel or electricity to pump the water from the riverside to a water reservoir tank situated above 70 m uphill from the river stream. Patil *et al.* [11] used the spiral coil pump as a low- to medium-head pump, and they experimented with a constructed coil pump in regard to wheel speed, layers of coil, and a submerged ratio. The experimental results showed that seven coils with a wheel diameter of 0.8 m gained 4.3 to 5 m head with 1200 dm^3/h discharge for one layer and 2280 dm^3/h for two layers, maintaining an efficiency of 20% to 74%.

A coil pump was designed and implemented by a group of students from Seattle University on the Zambezi River in Chirundu, Zambia, to supply water to a community for daily water needs. They claimed that their constructed coil pump is capable of supplying 30 liters of water per minute at a 10-meter elevation with a 30-meter onshore distance and this meets the needs for water of 200 residents [12]. Poudel *et al.* [13] proposed a water turbine pump (WTP) for the agricultural purposes of the Hill Track community in Nepal. The authors claimed that their designed WTP is capable of pumping 14 dm^3/s of water at a height of 14.9 m using a head of 3 m and a flow rate of 150 dm^3/s, with an efficiency of 50.5% [13].

A hydro-powered water pumping system is a self-contained stream-powered pump [14] with little maintenance cost, it is also known for easy construction, and a longer service life [15]. The hydro-powered coil pump is constructed and investigated for its various performance aspects in this work. The investigative analysis reveals that the coil pump with a v-notch and a 1″ delivery pipe shows better results in terms of discharge, power acquired, and water velocity through a channel compared to the coil pump with a 3/8″ delivery pipe.

2. Materials and methodology

2.1. Materials

Several instruments have been used for constructing the hydro-powered coil pump. Some of them, mainly the most important parts, are shown in Fig. 2. The instruments that are not indicated individually in this section are a pressure gauge with a tee joint, two elbow fittings, two unions, a pressure control valve, and a measuring tube.

2.1.1. Supporting frame. A structure of mild steel (MS) with 0.0508 m in width, shown in Fig. 2a, is constructed to support the wheel, shown in Fig. 2b. It is a moveable supporting frame that has been used for positioning the wheel at different locations from the notches at a certain distance, i.e., 18, 30, and 42 inches.

2.1.2. Wheel. A wheel shown in Fig. 2b with a radius of 0.152 m, containing 12 blades, four inlets (two inlets from each side), and two different outlets (separately used each at a time) with 1″ and 3/8″ internal diameter pipes, is used for the construction, and this wheel is mounted on the supporting frame.

2.1.3. PVC hose pipe. A flexible, clear, reinforced food-quality polyvinyl chloride (PVC) hose pipe measuring 4.87 m in length with five and a half turns

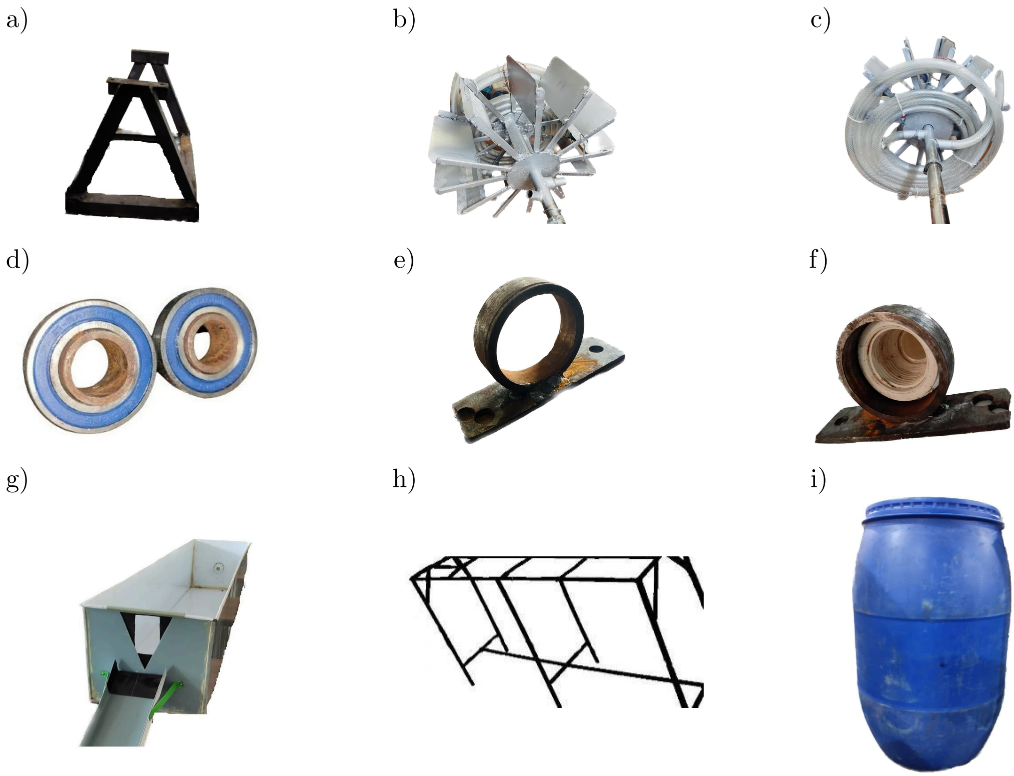

Fig. 2. Different parts of the constructed coil pump set-up: a) supporting frame, b) wheel, c) PVC hose pipe, d) ball bearing, e) bearing block, f) housing block, g) open channel, h) supporting structure, i) water reservoir.

is attached in a coiled manner, on both sides on the wheel shown in Fig. 2c. It is actually conveying water from the bottom line of the wheel to its center.

2.1.4. Ball bearing with blocks. A pair of ball bearings made of stainless steel (SS) with an outer diameter of 38 mm and an inner diameter of 25 mm, along with a bushing, shown in Fig. 2d, are used to assist the wheel in rotation and carrying load. Two bearing blocks is made from mild steel (MS), shown in Fig. 2e, to hold and support the bearing, and a PVC housing, shown in Fig. 2f, is implemented on the opposite side of the delivery pipe to prevent water leakage during the use of measuring tubes.

2.1.5. Open channel. An open channel with dimensions of 1.524 m × 0.3048 m × 0.254 m, shown in Fig. 2g, is constructed from an MS sheet through which water is moved. It has a v-notch and a rectangular notch located at the end of the channel, opposite to the water inlet side.

2.1.6. Supporting structure. Figure 2h shows a supporting structure made of MS measuring 1.57 m × 0.381 m × 0.762 m. This structure holds the entire open channel with a wheel and supporting frame.

2.1.7. Water reservoir. A 120-liter capacity plastic drum is used as the water reservoir, shown in Fig. 2i, from which water is circulating to the open channel through a pipe connected to an external motor pump, shown in Fig. 3.

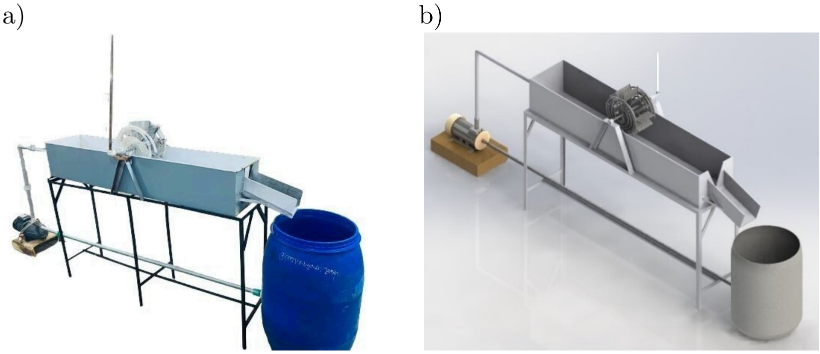

Fig. 3. Complete assembly of the hydro-powered coil pump: a) constructed, and b) designed.

2.2. Methodology

A complete set-up of the fabricated hydro-powered coil pump is shown in Fig. 3. A 1 HP external motor pump is used to draw water from the reservoir and deliver it to the open channel, placed on a structural support and regulated by a pressure control valve. After that, the complete set-up of the wheel with a hose pipe and different blocks is placed on the supporting frame. Next, this frame is located at different positions apart from the notches located on the opposite side of the water inlet in the channel. A 120-liter capacity water reservoir is placed after the notches. During the flow of water from the control valve to the reservoir side, the hydraulic energy of the water turns the wheel, and four inlets, two from each side, suck the water and supply it to the central pipe for subsequent discharge and measurement. Different measurements were taken by fully opening the valve (100%) and partially open (75%). At that time, the wheel was shifted with the frame at distances of 18, 30, and 42 inches from the notches. For each position, the depth of the wheel, rotation of the wheel, water velocity, water discharge, and manometric height of the water were recorded. The variables were the control valve opening, both for 100% and 75%, with a combination of a v-notch and a rectangular notch, as well as a 3/8″ and a 1″ delivery pipe for measuring manometric height.

2.3. Calculations

(i) When the flow control valve is fully (100%) open.

For v-notch:
when $H = 0.073$ m and $B = 0.073$ m:
area $A = \frac{1}{2}BH$
$= \frac{1}{2} \cdot 0.073 \cdot 0.073$
$= 0.00266\ \mathrm{m}^2$,
discharge $Q_t = \frac{8}{15} C_d \tan\frac{\theta}{2}\sqrt{2g}H^{\frac{5}{2}}$
$Q_t = \frac{8}{15} \cdot 0.62 \cdot \tan\frac{50}{2}\sqrt{2 \cdot 9.8} \cdot 0.073^{\frac{5}{2}}$
$= 0.000982\ \mathrm{m}^3/\mathrm{s}$,
velocity $V = \frac{Q}{A}$
$= \frac{0.000982}{0.00266}$
$= 0.3691$ m/s.

Similarly,
For $H = 0.072$ m and $B = 0.072$ m:
$A = 0.00259\ \mathrm{m}^2$,
$Q_t = 0.000949\ \mathrm{m}^3/\mathrm{s}$,
$V = 0.3664$ m/s.

For $H = 0.071$ m and $B = 0.071$ m:
$A = 0.00252\ \mathrm{m}^2$,
$Q_t = 0.000916\ \mathrm{m}^3/\mathrm{s}$,
$V = 0.3634$ m/s.

For rectangular notch:
when $H = 0.048$ m and $B = 0.057$ m:
area $A = BH$
$= 0.048 \cdot 0.057$
$= 0.00273\ \mathrm{m}^2$,
discharge $Q_t = \frac{2}{3} C_d B\sqrt{2g}H^{\frac{3}{2}}$
$Q_t = \frac{2}{3} \cdot 0.36 \cdot 0.057 \cdot \sqrt{2 \cdot 9.8} \cdot 0.048^{\frac{3}{2}}$
$= 0.0006369\ \mathrm{m}^3/\mathrm{s}$,
velocity $V = \frac{Q}{A}$
$= \frac{0.0006369}{0.00273}$
$= 0.2332$ m/s.

Similarly,
For $H = 0.046$ m and $B = 0.057$ m:
$A = 0.00262\ \mathrm{m}^2$,
$Q_t = 0.0005975\ \mathrm{m}^3/\mathrm{s}$,
$V = 0.2280$ m/s.

For $H = 0.045$ m and $B = 0.057$ m:
$A = 0.00256\ \mathrm{m}^2$,
$Q_t = 0.0005781\ \mathrm{m}^3/\mathrm{s}$,
$V = 0.2258$ m/s.

(ii) When the flow control valve is partially (75%) open.

The corresponding values are calculated using the above equations for both v-notch and rectangular notch.

For v-notch:
when $H = 0.071$ m and $B = 0.071$ m,
$A = 0.00252\ \mathrm{m}^2$,
$Q_t = 0.000916\ \mathrm{m}^3/\mathrm{s}$,
$V = 0.363$ m/s.

Similarly,
for $H = 0.070$ m and $B = 0.070$ m,
$A = 0.00245\ \mathrm{m}^2$,
$Q_t = 0.000884\ \mathrm{m}^3/\mathrm{s}$,
$V = 0.360$ m/s.

For $H = 0.069$ m and $B = 0.069$ m,
$A = 0.00238\ \mathrm{m}^2$,
$Q_t = 0.000853\ \mathrm{m}^3/\mathrm{s}$,
$V = 0.358$ m/s.

For rectangular notch:
when $H = 0.045$ m and $B = 0.057$ m,
$A = 0.00256\ \mathrm{m}^2$,
$Q_t = 0.0005781\ \mathrm{m}^3/\mathrm{s}$,
$V = 0.225$ m/s.

Similarly,
for $H = 0.044$ m and $B = 0.057$ m,
$A = 0.00250\ \mathrm{m}^2$,
$Q_t = 0.000558\ \mathrm{m}^3/\mathrm{s}$,
$V = 0.223$ m/s.

For $H = 0.043$ m and $B = 0.057$ m,
$A = 0.00245\ \mathrm{m}^2$,
$Q_t = 0.000540\ \mathrm{m}^3/\mathrm{s}$,
$V = 0.220$ m/s.

3. Results and discussion

3.1. Fully opened (100%) control valve

Different data found during the constructed coil pump operation are listed in Tables 1 and 2. Operational characteristics values are presented in Table 2, while the depth of the wheel, rotation of the wheel, and water velocity are shown in Table 1, both for the 1″ and 3/8″ delivery pipes.

Table 1. Wheel depth, rotation, and water velocity of constructed coil pump for 100% control valve opening.

Position of wheel from notch [inch]	Wheel depth in water [m]	Wheel rotation [rpm]		Water velocity [m/s]		Control valve opening (100%)
		v-notch	Rectangular notch	v-notch	Rectangular notch	
42	0.043	42	40	0.369	0.233	(3/8)″ DP
						1″ DP
30	0.045	28	28	0.366	0.228	(3/8)″ DP
						1″ DP
18	0.050	18	20	0.363	0.226	(3/8)″ DP
						1″ DP

Table 2. Discharge, manometric height, and power of constructed coil pump for 100% control valve opening.

Position of wheel from notch [inch]	Discharge [m^3/s]		Manometric height [m]		Power [W]		Absolute power difference [W]	Control valve opening (100%)
	v-notch	rn*	v-notch	rn*	v-notch	rn*		
42	0.0066	0.0055	0.51	0.51	33.0204	27.5170	5.5034	(3/8)″ DP
	0.0125	0.0105	0.30	0.29	36.7875	29.8714	6.9161	1″ DP
30	0.0038	0.0039	0.37	0.37	13.7928	14.1558	0.3630	(3/8)″ DP
	0.0075	0.0070	0.16	0.16	11.7720	10.9872	0.7848	1″ DP
18	0.0030	0.0030	0.31	0.32	9.1233	9.4176	0.2943	(3/8)″ DP
	0.0050	0.0045	0.10	0.09	4.9050	3.9730	0.9320	1″ DP

*rn – rectangular notch.

From Fig. 4a, it is observed that the velocity of water through the open channel has varied significantly for v and rectangular notches. In the case of the v-notch, it is almost 1.5 times greater than the velocity for the rectangular notch. However, the variations in wheel rotation are insignificant, both for the v and rectangular notch. The maximum water velocity was observed at 0.369 m/s

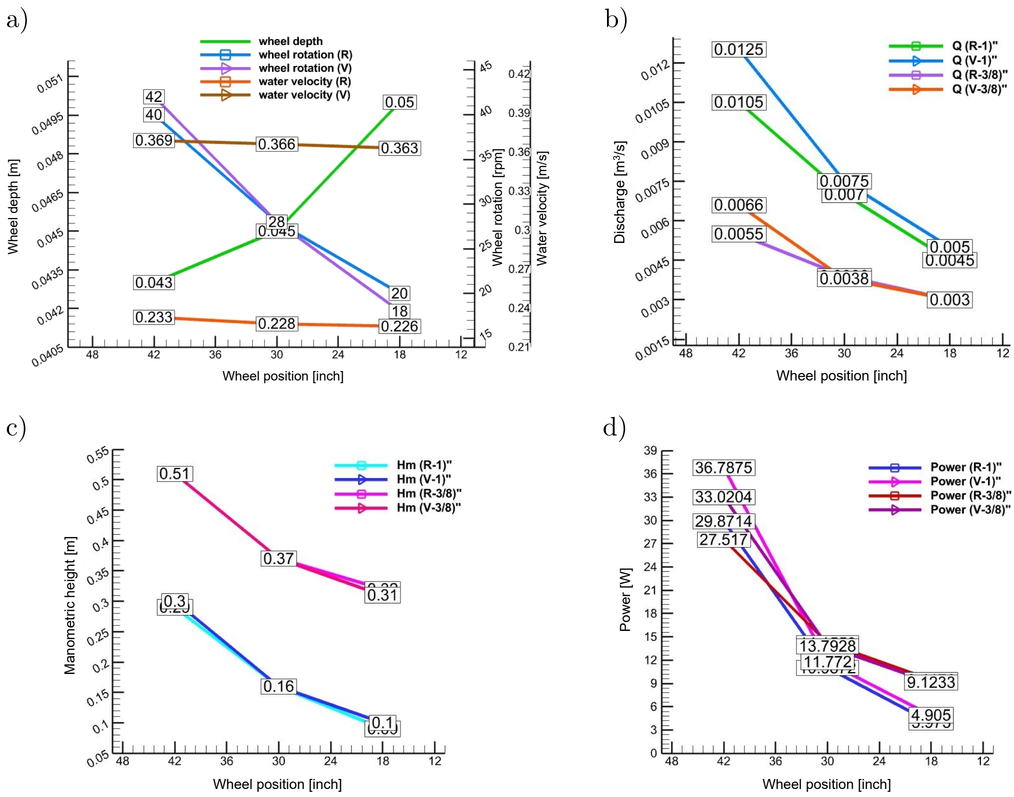

FIG. 4. Diagram of fully opened (100%) control valve for wheel position V_s: a) wheel depth, wheel rotation, and water velocity, b) discharge, c) manometric height, and d) power.

for the v-notch, and the minimum velocity was found at 0.226 m/s for the rectangular notch.

Operational parameters, such as discharge through the delivery pipes, are presented in Fig. 4b. The figure shows that a larger diameter of delivery pipes when using a v-notch will provide a higher discharge compared to the same delivery pipes with rectangular notches. In the case of a 3/8″ delivery pipe, after a certain time, the discharge for both cases becomes almost identical. However, for the 1″ delivery pipe, the maximum water discharge is 0.0125 m^3/s for the v-notch, while for the rectangular notch, it is 0.0105 m^3/s. In the case of the manometric height shown in Fig. 4c, the maximum height is observed for the 3/8″ delivery pipe, as expected from the power equation of a pump. Both the v and rectangular notch with the same delivery pipe have almost identical values of a maximum of 0.51 m for the 3/8″ delivery pipe and 0.3 m for the 1″ delivery pipe. The power curve shown in Fig. 4d was obtained using the head and discharge of the coil pump. Similar to the discharge and water velocity, the power obtained from the constructed coil pump is maximum for the v-notch, with 36.7875 watts for the 1″ delivery pipe. Although the power acquired by the pump from water decreases as the wheel moves away from the water inlet side on the channel, the rate of declining power for the 3/8″ delivery pipe has a lower margin compared to its initial values, as well as the 1″ delivery pipe.

3.2. Partially opened (75%) control valve

In Tables 3 and 4, performance characteristics such as manometric height for both the 1″ and 3/8″ delivery pipes, discharge through the v and rectangular notches, water velocity in the channel, wheel rotation, and depth of the wheel in water is presented against the position of the wheel on the open channel apart from the notches of the constructed hydro-powered coil pump.

Table 3. Wheel depth, rotation, and water velocity of constructed coil pump for 75% control valve opening.

Position of wheel from notch [inch]	Wheel depth in water [m]	Wheel rotation [rpm]		Water velocity [m/s]		Control valve opening (75%)
		v-notch	Rectangular notch	v-notch	Rectangular notch	
42	0.041	39	37	0.363	0.225	(3/8)″ DP
						1″ DP
30	0.043	25	25	0.360	0.223	(3/8)″ DP
						1″ DP
18	0.048	15	16	0.358	0.220	(3/8)″ DP
						1″ DP

Table 4. Discharge, manometric height, and power of constructed coil pump for 75% control valve opening.

Position of wheel from notch [inch]	Discharge [m^3/s]		Manometric height [m]		Power [W]		Absolute power difference [W]	Control valve opening (75%)
	v-notch	rn*	v-notch	rn*	v-notch	rn*		
42	0.0055	0.0055	0.48	0.48	25.898	25.898	0.0000	(3/8)″ DP
	0.0125	0.0105	0.26	0.29	31.882	29.871	2.0110	1″ DP
30	0.0033	0.0039	0.33	0.33	10.683	12.625	1.9420	(3/8)″ DP
	0.0075	0.0070	0.12	0.16	8.8290	10.987	2.1580	1″ DP
18	0.0027	0.0030	0.28	0.29	7.4163	8.5347	1.1184	(3/8)″ DP
	0.0050	0.0045	0.07	0.09	3.4335	3.9730	0.5395	1″ DP

*rn – rectangular notch.

Utilizing the data from Table 3, Fig. 5a is plotted for wheel position vs. wheel depth, wheel rotation, and water velocity. From the figure, it is noticeable that the water velocity through the channel, in the case of v-notch implantation, is almost 1.5 times higher compared to the rectangular notch, although the rotation of the wheel for both cases has not varied notably. It is also observed that by shifting the wheel towards the notches from the water inlet, wheel rotation decreases from 39 rpm to 15 rpm for the v-notch and from 37 rpm to 16 rpm for the rectangular notch. Similarly, water velocity decreases from 0.363 m/s to 0.358 m/s for the v-notch and from 0.225 m/s to 0.220 m/s for the rectangular notch. Overall, no effects have been observed for the variation in the diameter of delivery pipes. Figure 5b has been derived from Table 4, indicating the water discharge through both delivery pipes against different positions of the wheel. It suggests that there are almost the same discharges for the 3/8″ delivery pipe when using both v and rectangular notches. But, in the case of the 1″ delivery pipe, the v-notch shows a better discharge with 0.0125 m^3/s compared to the

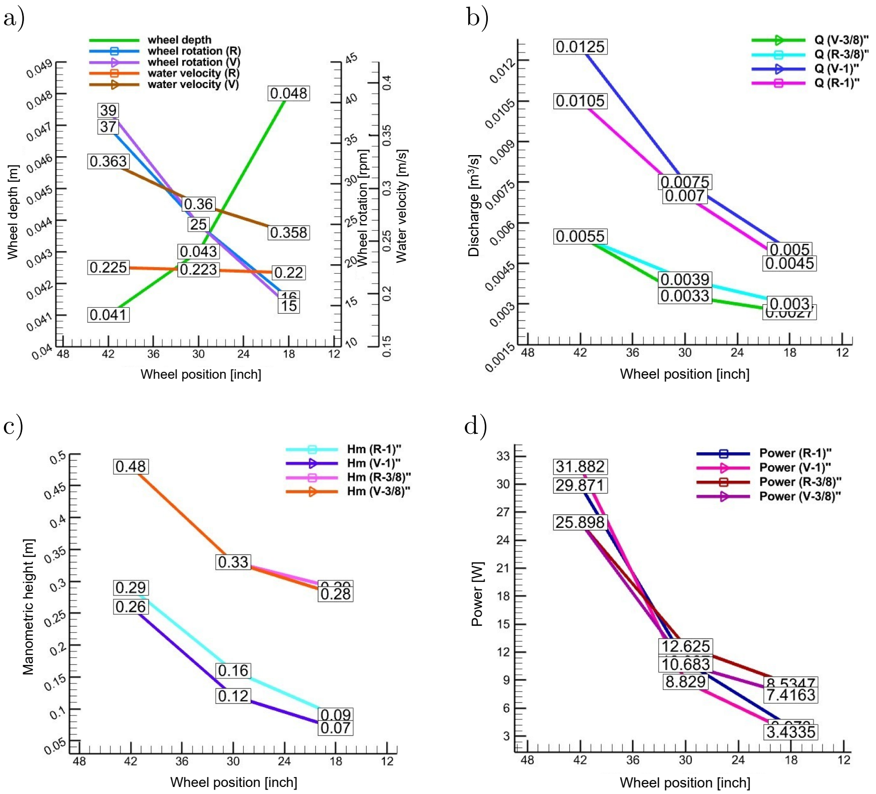

FIG. 5. Diagram of partially opened (75%) control valve for wheel position V_s: a) wheel depth, wheel rotation and water velocity, b) discharge, c) manometric height, and d) power.

rectangular one with 0.0105 m^3/s. On the other hand, the $3/8''$ delivery pipe displays a better manometric head of 0.48 m than the $1''$ delivery pipe's head of 0.29 m, as shown in Fig. 5c. The power in watts, displayed in Fig. 5d, is measured from the discharge and manometric head from Table 4. It is observed that the fluid power generated by the constructed coil pump decreases as the wheel moves far away from the water inlet side of the channel. The maximum and minimum power are found at 31.882 W and 3.4335 W, respectively, for the $1''$ delivery pipe with a v-notch. But in the case of the $3/8''$ delivery pipe, power fluctuations are smaller than in the $1''$ delivery pipe.

4. Conclusion

The potential of hydroelectric energy is very big so it can easily meet the current energy demand of the world alone if the maximum possible energy is harnessed from these sources of energy. Extracting hydropower using its stream motion is one of the different categories. Thus, a laboratory-based prototype of a hydro-powered spiral coil pump has been constructed and implemented to investigate the performance of the pump. In the study, it was found that:

i) Increasing the submerged ratio of the wheel to water decreased the rotational speed of the wheel.
ii) Positioning the wheel towards the water inlet side increased the water discharge rate, manometric height, and power through the coil pump.
iii) The coil pump with a v-notch and a $1''$ delivery pipe shows better results in terms of discharge, power acquired, and water velocity compared to the coil pump with a $3/8''$ delivery pipe. But, in terms of the capability of pumping water at maximum manometric height, a rectangular notch with a $3/8''$ delivery pipe performs better than the v-notch.

Author contributions

All the authors of this research have contributed significantly to the work submitted. Conceptualization, M.A.H.; original draft writing and preparation, M.A.H., M.R, and S.I.F.; review and editing, M.A.H, M.R, and S.I.F. All authors have agreed and read the accepted and published form of the manuscript.

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Data availability statement

All data are available in the paper.

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Conflicts of interest

The authors declare no conflict of interest.

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