Turbine Design and Its Impact on Energy Harvesting from In-Pipe Hydro Systems

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***Abstract*—This paper aims at investigating the impact of the utilized turbine design on the harvested energy from in-pipe systems. Four turbine designs are involved in this study which includes the spherical turbine and the Helical (Egg Beater) with three blades, four blades, and five blades. The proposed turbines are designed and they have been implemented in a prototype to determine the performance of each design. The study presents design procedures and the design requirements of each employed turbine before the implementation phase. The next step is to collect the produced torque, rotational speed, pressure drop, and output power for each turbine experimentally. The results have been analyzed and compared to show the design impact on these parameters. Finally, a case study is carried out on the major water distribution network in Amman the capital of Jordan to determine the possible locations, which are benefited from the implementation of the in-pipe system with the examined turbines.**

***Index Terms*—in-pipe system, energy harvesting, turbine design**

I. Introduction

Hydropower is considered as a developed and a cost-competitive renewable energy source, in which energy and water are linked strongly together. Indeed, significant energy is used to deliver the water to the consumers throughout the distribution system. This excessive energy might damage the transporting pipes at some points due to the extra pressure. Therefore, pressure valves are used to reduce the pressure in these pipes to proper levels. The excess pressure points can be exploited by generating clean energy that supplies different loads near to these points. The inclusion of the turbines in the distribution pipe will reduce the system cost significantly due to not using pressure valves. In this technology, the pipe is equipped with a turbine, which is connected to a generator, which is mounted on top of the pipe. The generated energy from the in-pipe system is known in the literature by in-pipe hydropower [1-3].

Unlike traditional renewable energy resources, the in-pipe hydropower energy is independent of the weather changes, and it is classified as an environmentally friendly energy source. Moreover, it is known as one of the cheapest means to produce energy regarding installation and maintenance cost. One of the critical design issues that must be considered during the design of Hydrodynamic turbines is to maximize the power production without disturbing the water flow in the distribution network [4].

The in-pipe hydropower systems are classified into two main designs according to the location of installation. In the internal system, the entire runner is placed vertically inside the pipe, and the generator is placed outside which provides design simplicity. On the other hand, the runner is connected in a secondary line in case of external system and it is independent of the pipe size, which allows higher flexibility, higher efficiency and lower operating and maintenance cost. Moreover, the turbine can also be classified based on its operation principle. The reaction turbine is used in low head sites, and it reacts to the high fluid issuing from nozzles to rotate the turbine according to Newton's third law. Whereas, the impulse turbine produces the work from the fluid issuing on a series of blades and it is typically used in high head sites.

In this work, the investigated turbines belong to internal system and reaction turbines. After determining the turbine location and the operation conditions, the used designs must be specified. In the literature, several blade designs have been proposed based on the shape of the blades and the connection of the turbine with the shaft. For instance, the H-Darrieus is one of the used turbines to convert the wind energy into electrical energy, and it provides good performance in contrast to the other used turbines. Another turbine design which is known by Darrieus turbine, which is a vertical axis turbine and it has streamlined blades turning around an axis perpendicular to the flow.

The turbine consists of a group of curved blades which allow the blade to be stressed only in tension at high rotating speeds [1]. The designed turbines in this work are the spherical turbine with three blades, four blades and with five blades. The used design is a combination of the Darrieus wind turbine and Gorlov turbine (Egg-beater). The design and implementation of the proposed turbines will be presented in the next sections.

II. Designed Turbines

In this section, SolidWorks is used to design multiple turbines that consist of three and four blades; each design has a different angle of attack to evaluate the most efficient design, to be used in the prototype. A spherical turbine was designed to rotate transversely within a cylindrical pipe,

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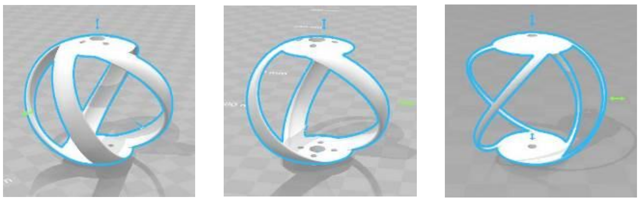
which is coupled with a generator. In one embodiment, the blades of the spherical turbine curve in an approximately 180-degree arc in a plane that is at an inclined angle relative to the rotational axis of a central shaft. The design of lucid energy turbine [5] was modified, and three designs have been proposed as shown in Table I.

The aim of proposing several designs is investigating the main parameters, which affect the turbine performance. These parameters include the number of blades, the angle of attack, the width of the blade, and the employed material, which forms the blades. The next step was preparing the designed models for a 3D printing phase as depicted in Fig. 1.

TABLE I. COMPARISON OF DESIGN PARAMETERS OF SPHERICAL TURBINES

	Design 1	Design 2	Design 3
Angle of Attack	12 °	15 °	15 °
Number of Blades	4	3	4
Blade Width	5 mm	6 mm	6 mm
Material	PLA	PLA	Photocurable resin
Diameter	49.5 mm	49.5 mm	49.5 mm

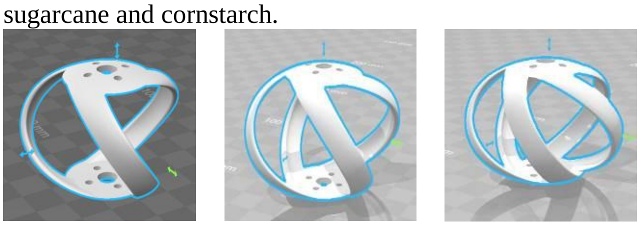
The second proposed design is a combination of the Darrieus wind turbine and the Gorlov turbine (H-Egg). The shape is longitudinal along the vertical axis, and the airfoil blade profile is swept in a helical profile along its span. Again, the main parameters that affect the turbine performance have been investigated. Fig. 2 depicts the proposed designs and Table II compares between the three models.



(a) (b) (c)

Figure 1. Proposed designs of spherical turbines (a) Design No. 1 with four blades, (b) Design No. 2 with three blades, (c) design No. 3 with four blades.

The blades have been designed using SolidWorks software; the turbines were 3D-printed by adding material layer by layer based on advanced technology that builds up parts in layers at the sub-mm scale. The used material in the 3D printing process was Poly Lactic Acid (PLA) and it is made out of organic material, which mainly contains sugarcane and cornstarch.



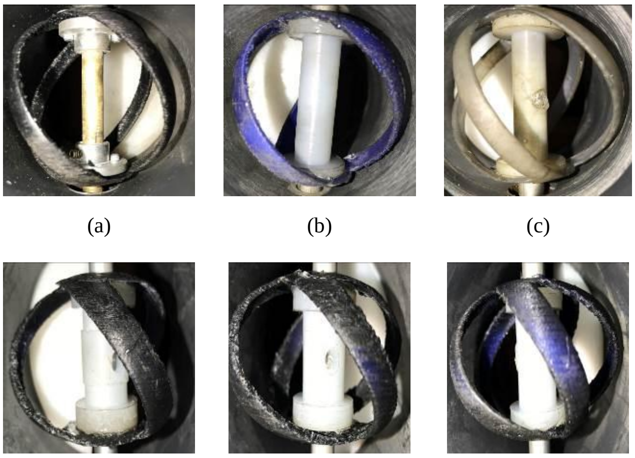
(a) (b) (c)

Figure 2. Proposed Gorlov (H-Egg) turbine designs (a) Design No. 4 with three blades, (b) Design No. 5 with 4 blades, (c) Design No. 6 with five blades.

This material was chosen due to its safety and the ease to use, and it provides a smooth finishing. Moreover, another material has been investigated in the 3D printing for one of the designed turbine, which is Photocurable resin. This material is lighter and more elastic than PLA, but it is more expensive. The Fig. 3 below shows the 3D-printed turbines of the designs as mentioned earlier.

TABLE II. COMPARISON OF DESIGN PARAMETERS OF GORLOV (H-EGG) TURBINES.

	Design 4	Design 5	Design 6
Angle of Attack	12 °	15 °	12 °
Number of Blades	3	4	5
Blade Width	7 mm	7 mm	7 mm
Material	PLA	PLA	PLA
Vertical Axis	31.5 mm	33.5 mm	31.5 mm
Horizontal Axis	49.5 mm	49.5 mm	49.5 mm



(a) (b) (c)

(d) (e) (f)

Figure 3. D-printed turbines; (a) Spherical turbine with four blades, (b) Spherical three blades, (c) Spherical four blades, (d) H-Egg three blades, (e) H-Egg four blades, (f) H-Egg five blades.

III. PROTOTYPE DESIGN

In this section, a prototype to mimic the in-pipe hydropower system was implemented as demonstrated in Fig. 4. The system consists of a tank for water storage, PVC pipe which acts as a connection between the tank with submersible pump passing through the turbine segment and then back to the tank to close the loop. A submersible pump is then used to pump the water and to increase the pressure of water inside the pipes; the gate valve is used to manipulate the water flow rate. The pipe adapter (also called a coupler) is used to connect the 3.17 mm outlet diameter of the pump to the 63 mm pipe diameter. PVC sleeves and elbows are also implemented to connect the pipes. The support structure was designed with one-meter height to take advantage of the gravity fed. This height is selected to generate a pressure of approximately 0.1 bar in addition to the pressurized pumped water.

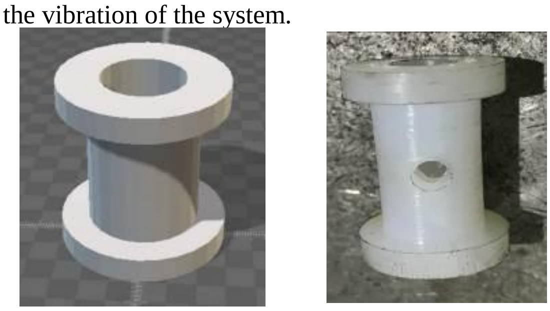
Finally, the steel angles are used to withstand the weight of the tank. Fig. 5 (a), and Fig. 5 (b) show the considered turbine segment from outside, and inside, respectively. This segment extends to 10 cm long, and it is attached with rubber sleeves from each side to be connected with the rest of the loop. The turbine diameter was selected to be 49.5mm, and it was printed with a hole in the middle for the shaft, which would go through the turbine and the bearing and then out of the pipe to be connected to the DC generator. Other holes were also printed for the flange screws. The length of the shaft was 6 mm, and it was made of steel.

Figure 4. Implemented prototype to mimic the in-pipe hydro system; the system consists of tank, submersible pump, flow control valve, DC generator, speed sensor and Wattmeter.

(a) (b)

Figure 5. Turbine segment/ outside, (b) Turbine segment/ inside

The flange was used as a connector between the turbine blades and the shaft to transfer the rotational motion of the blades to the shaft. The Flange was designed using CATIA V5, as shown in Fig. 6. The top flange is connected to the bottom flange by a shaft which has a hole in the middle to hold the main shaft which will ease the rotation and reduce the vibration of the system.



(a) (b)

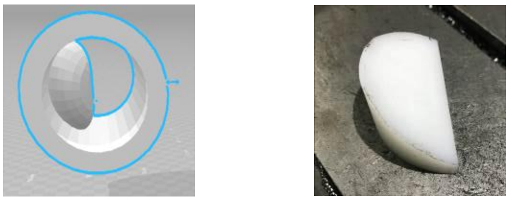
Figure 6. (a) Flange design using CATIA software, (b) Implemented flange.

The shaft was connected to ball bearings at the intersections of the pipe. The designated bearings in the prototype were 606 with rubber sealing to reduce rotational friction and to support axial and radial loads [6]. The outer race of the bearing was stationary with a diameter of 17mm. The inner race was connected to the shaft with a diameter of 6mm. These bearings were can be located in a cylindrical box as shown in Fig. 7.

Furthermore, a deflector was used in the system to increase the efficiency by around 30 - 40% by concentrating the flow at one side of the turbine; and this will increase the produced torque by the turbine [7-9]. The deflector will also increase the velocity of the water flow by decreasing the area based on the continuity equation [10]. The deflector was designed using CATIA V5 with an angle of 35° as shown in Fig. 8.

(a) (b)

Figure 7. (a) Cylindrical box design view 1, (b): Cylindrical box design view 2



(a) (b)

Figure 8. (a) Designed deflector using CATIA V5, (b) Implemented deflector

IV. Experimental Results

In this section, the empirical results of the proposed turbines have been summarized in Table 3, where the power was varying with the used model design. The output power in in-pipe hydropower system in case of gravity fed structure can be estimated using the following formula [8], [11]:

$$P=\eta\times\rho\times H\times Q\times g\,. \tag{1}$$

where,

$P \equiv$ The output power [W]

$\eta \equiv$ Turbine efficiency

ρ = Water density $\left(1000\text{kg}/\text{m}^3\right)$

H = Net head (m)

Q = Water flow rate $\left(\text{m}^3/\text{s}\right)$

g = Gravity acceleration constant $\left(9.8\text{m}/\text{s}^2\right)$.

The torque was calculated using the following Equation.

$$P=\omega\times\tau \tag{2}$$

where,

P = The output power (W)

ω = Angular velocity of the shaft (rad/s)

τ = Produced torque (N/m).

The speed in rpm was measured using a tachometer, and the pressure was measured using a Differential Pressure (DP) transmitter. The speed in (rad/s) was calculated using the following Equation.

$$\omega = \frac{2\pi N}{60} \tag{3}$$

where,

N ≡ revolution per minute (rpm).

The flow rate was measured using the flow meter with the Arduino. The spherical turbines with three and four blades presented poor performance; therefore, they have been excluded from the study.

The output power of the remained turbines has been measured and analyzed versus the pressure drop as shown in Fig. 9. It was observed that the increment of the pressure drop at the turbine segment yield in an increase in the generated power. For instance, the spherical turbine with four blades was delivering 16 Watt at approximately 60 mbar pressure drop at the turbine segment. This value was the best result that has been obtained among the proposed designs. The generated power of the other turbines was smaller as depicted in Fig. 9.

The produced torque for each turbine design was measured and the results have been summarized in Fig. 10 (a). The results show that the produced torque is dependent on turbine design and the pressure drop. Hence, the more pressure drop on the turbine, the more torque the system will produce. The spherical turbine with four blades offered the highest-pressure drop with a produced a torque of 0.44 N.m. Fig. 10 (b) shows the power produced by each turbine. It can be noticed that the spherical turbine with four blades produced the highest power value of 16 Watt, and the H-Egg 3 blades produced the lowest power value of almost 1 Watt.

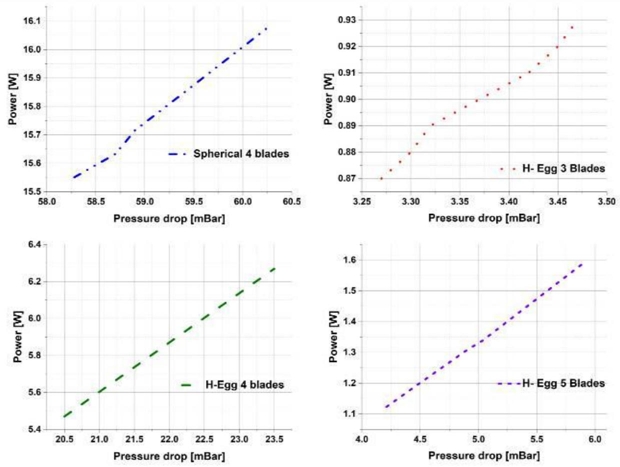
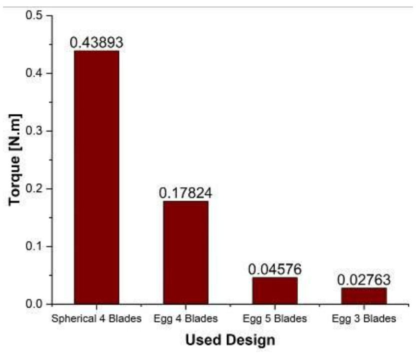


Figure 9. Power vs. pressure drop for proposed designs

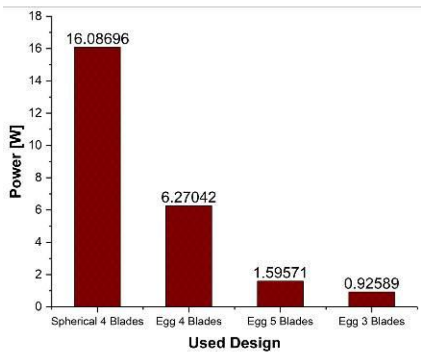
Fig. 10 (c) displays the pressure drop caused by each turbine. The pressure drop was varying with the attack angle, the number of blades, and the shape of the turbine. Each shape has an optimum attack angle, increasing or decreasing this angle will negatively affect the pressure drop. The flow rate was constant at 160 L/min, as measured by a flow meter. Fig. 10 (d) shows the shaft speed for each turbine. It was observed that the angular shaft speed depends on water flow, which was almost the same for each turbine since the water flow was constant.

TABLE III. TESTED TURBINES RESULTS

Design	Speed (rpm)	Speed (rad/s)	Torque (N.m)	Pressure drop (mbar)	Pressure drop (m)	Flow rate (L/min)	Flow rate (m3/s)	Power (Watt)
Spherical turbine 4 blades	350	36.65	0.439	60.29	0.615	160	0.0027	16.09
H-Egg 4 blades	336	34.18	0.178	23.5	0.24	160	0.0027	6.27
H-Egg 5 blades	333	34.87	0.046	5.92	0.06	160	0.0027	1.6
H-Egg 3 blades	320	33.51	0.028	3.47	0.038	160	0.0027	0.93



(a)



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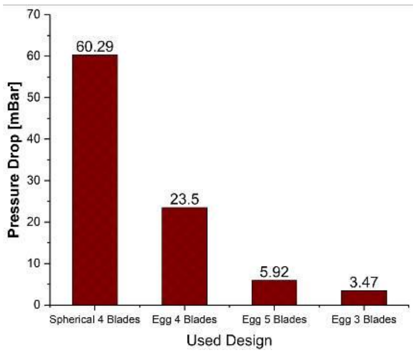
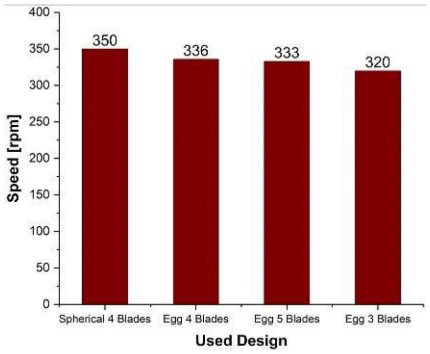


(c)



(d)

Figure 10. Produced torque versus proposed design, (b) Output power versus proposed design, (c) Pressure drop versus proposed design, (d) angular speed of the shaft versus proposed design.

V. Amman Water Distribution Network Case Study

As a case study, the primary water distribution network in Amman (the capital of Jordan) is considered to determine the possible locations, which can be benefited from the implementation of the in-pipe system with the examined turbines. The water network is divided into three main parts: Primary pipes (located in Disi water, Zai station, Alzara Ma'een, and Water wells), Secondary pipes (e.g., the pipe between Dabouq and Al Akhdar), and Territory pipes (e.g., a territory plan from Abu Nusair to Shafa Badran). Table IV shows the distribution network for main tanks in Amman. Table IV. Distribution network for main tanks in Amman

Table V illustrates the possible locations and the collected data of the pressurized water using the best-proposed turbine design (i.e., spherical turbine with four blades), the estimated output power was calculated by employing the pressure drop in the desired pipes. To calculate the output power, Equation (1) is used.

TABLE IV. Distribution Network for Main Tanks in Amman.

Location	Capacity (m^3)	Elevation (m)	Max. Flow (m^3/s)	Pipes Diameter (mm)
Dabouq	250,000	1,030	0.2778	1000-800
Al Akhdar	5000	800		
Shafa Badran Upper	1000	980	0.1388	400
Shafa Badra Lower	1000	920		

TABLE V. Possible Locations to Install the System in Amman.

Location	Pipe diameter (mm)	Flow rate (m^3/s)	Pressure drop (m)	Output power (kW)
Shafa Badran upper and lower	400	0.1388	3.886	5.291
Dabouq – Al Akhdar (1)	1000	0.2778	9.714	26.47
Dabouq – Al Akhdar (2)	800	0.2778	7.77	21.7

Fig. 11 depicts the estimated results for the specified locations in Amman. The results showed that the implementation of the spherical turbine with four blades in the in-pipe network between Dabouq and Al-Akhdar could produce the maximum power compared to the other locations. The estimated power in the case as mentioned earlier is expected to reach 26.6 KW of green energy.

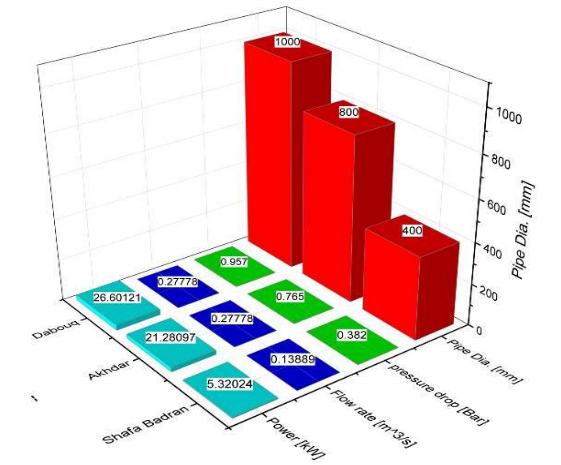


Figure 11. Estimated results for the specified locations in Amman

VI. Conclusion

In this work, several turbine designs have been proposed for the in-pipe hydro system. The performance of the proposed designs was compared by implementing them in a real prototype that mimics the in-pipe system with gravity fed structure. The generated power depends on converting the extra water pressure in the in-pipe system to green power which can be used later to feed secondary applications such as lighting or any other loads. Six turbines were proposed and investigated, and they have been implemented using SolidWorks software and a 3D printer. The design factors, which have been addressed in this work phase, were the number of blades, the angle of attack and the thickness of the blade. Each turbine was tested separately to determine the pressure drop and the generated output power. According to the experimental results, the spherical turbine design presented better performance in comparison with the Hybrid H-Egg designs since the blades had larger frontal area. Hence, more water streamlines were hitting the blades which leads to higher rotational speed. The output power of 16 W was obtained from the four blades spherical turbine, which is a good result from a small prototype. The proposed designs are recommended for implementation in-pipe hydro system, and mainly they can be used in the locations of that require pressure reduction as an alternative for pressure control valves. Moreover, a case study was conducted to investigate the benefit of the proposed system in the water network in Amman-Jordan. It is found that the system can be installed in several locations and it can produce up to 26 kW. Finally, the system is expected to provide higher energy and to occupy less area in contrast to the PV system and wind turbines.

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