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Production of electricity employing sewerage lines using a micro cross flow turbine

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Abstract

In the design of cross flow turbines, efficiency is a significant parameter. The crossflow turbine for developing nations is the most cost-efficient electricity generation source and often used in isolated power systems. This research work analyzes the potential of electricity production using a micro-cross flow turbine from sewage lines. To measure the hydraulic potential of the sewage's wastewater, flow rate at the connection point was investigated by experimentation on site and the efficiency of the micro cross flow turbine was evaluated. The experimental results show that the hydraulic potential of the selected point for electricity production is enough throughout the year. It also shows that the micro-cross flow turbine can be used effectively to produce electricity from the sewage at the link points. The highest efficient 2 mm head was observed with a maximum flow rate of 0.112 m^3/s. Depending on the flow rate, the turbine velocity was 103-263 rpm. The maximum power of shaft was 284.58 W and the highest power generated was 196.24 W. The maximum overall efficiency was 68.2%. This article discusses the design, efficiency, operation and cost of low-head micro crossflow turbines.

Keywords: Electricity Generation, Hydraulic Potential, Micro Cross Flow Turbine, Sewage

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1. Introduction

In today's global renewable energy, the role of hydro plants is becoming critically important. The cost-effective way of supplying electricity to streetlights can be the small scale renewable energy sources, which helps to reduce the domestic grids load (Nakase *et al*., 2014; Chen and Choi, 2013). The immense dependence on conventional energy sources had severe environmental impacts and power outages, which have raised the worldwide consciousness for renewable resources (Acharya *et al*., 2015). Hydropower is a major and sustainable renewable energy source among several other renewable sources which can be utilized due to its appealing economics and the accessibility of fundamental technology. Among the hydropower systems the CFMT is the most preferable. A turbine essentially turns hydraulic power by rotating shaft into mechanical power (Adhikari and Wood, 2018). The power transmission is carried out through blades (Alexander *et al*., 2009). Currently, because of its easy design and manufacturing, the crossflow micro turbines in low head and low water flow rates are used. A standard Cross-Flow Turbine comprises of two major parts, the nozzle and the runner moreover cross flow turbine performance is strongly influenced by turbine structure configuration and flow characteristic on turbine blades, nozzle geometry, blade inclination and number of turbine blades (Aplicada, 2004). The angle of the runner serves as a absorber to capture the kinetic energy of the water that strikes the surface of the blade causing the runner to convert that energy of the water into mechanical energy (Aree, 2013).

Sewage consists of rainwater and water which human beings and manufacturing operations release to the sewer (Cabra, 2014). The wastewater consists of human waste from homes, workstations and industrial sector is included in the sewer system. The annual waste-water generation in the Islamic Republic of Pakistan is estimated at 6,414 billion m^3 (BCM), consisting of 4,953 BCM of municipalities annually and of 0,395 BCM of industrial products annually (Chichkhede *et al*., 2016), also waste water of 0.886 billion cubic meter per year is being directly used for irrigation purpose in farming sector. The irrigation land served by waste water is 33610 hectors (Dakers and Martin, 1982). The article aims to use sewage as a source of energy. Waste water sludge utilization is negligible in Pakistan, the number of sewage treatment facilities Multan region is 11, and there is none small-hydraulic power plant to utilize this sewage potential (Date and Akbarzadeh, 2009). Water treatment systems include drainage systems like sewage pipes, treatment equipment like treatment plants and additional installations such as pump stations.

The complete length of waste water pipes of Multan region in Fiscal Year 2011 was about 9.79 * 106 km (Desai, 1993). Hydraulic energy potential is therefore assumed to be scattered throughout the country in sewage pipes (Diego and Restrepo, 2012). As a result, the use of drainage waste for electricity production which could contribute to the local electrical power production as local consumption is immense (Diez, 2008). But this generation of sewage energy has never taken place and the hydraulic energy potential has not been studied in the drainage plants in Pakistan (Elbatran *et al*., 2015; Falconi *et al*., 2009; Ghalichechian *et al*., 2008; Ikeda *et al*., 2010; Jeon *et al*., 2005). Thus the desire to achieve hydraulic micro-scale electricity production with an energy output of less than 90 kW is growing (Alexander *et al*., 2009; Singh and Nestmann, 2011; Stark *et al*., 2011; Yasuyuki *et al*., 2014; Runner, 2015; Uchiyama *et al*., 2016).

Such area units for micro-hydraulic turbines often contained foreign material such as dropped leaves, twigs, human and animal waste. The foreign matter can be removed from a filter installed at the start of the micro-hydraulic turbine. However, the operational costs of such machinery increased due to additional components. We are committed to developing a MCFT that is outstanding in terms of foreign matter passage without stirring the effectiveness of cross flow turbine (San and Nyi, 2018; Uchiyama *et al*., 2018). The runner has a cavity around the main axis to allow waste matter passage. Wastewater includes both home-based hair and vegetable waste, kitchens and human waste. It is important that turbine is not blocked by waste matter to effectively produce energy from sewage (Sinagra *et al*., 2014). Therefore, the micro cross flow turbine, we are developing pledges to be efficient for sewage electricity production.

Several research studies were conducted to develop the optimum setup of the crossflow turbine, both by experimental and numerical methods. Most of the research contains information regarding impact on the shape of the nozzle, the ratio of diameter of the runner, the inlet arch and the number of turbine blades. Sinagraa *et al*. (2014) outlined a straightforward and thorough procedure for the design and discharge of a crossflow turbine. In this document a basic but stringent method was described to design a crossflow turbine with a discharge control unit. The authors noted reduced turbine effectiveness, minimized surface inlet and simulated fluid dynamics. The theoretical framework of the synchronous design of turbine parameters was developed by Vincenzo *et al*. (2012) and the new computing capabilities were fully exploited. Table 1 sums up the significant prior research (Murtaza, 2010; Nasir, 2015; Asia, 2009; Patel, 2016; Paul, 1997; Pareira. 2009; Prajapati, 2015; Ranterarung, 2018; Reihani, 2014; Ricardo, 2007; Desai, 2015).

Table 1. Previous Research Work

Source	***d***	^{b}**1b**	**R_2/R_1**	**N_b**	***q_s***	***h***
	(deg)	**(deg)**	**(-)**	**(-)**	**(deg)**	**(%)**
Macmore and Merryfield (1949)	16	30	0.66	20	-	68
Varga (1959)	16	39	0.66	30	-	77
Durali (1979)	16	30	0.68	24	-	76
Dakers and Martin (1982)	22	30	0.67	20	69	69
Johnson *et al*. (1982)	16	39	0.68	18	60	80
Nakase *et al*. (2014)	15	39	0.68	26	90	82
Durgin and Fay (1984)	16	39	0.68	20	63	66
Khosrowpanah *et al*. (1988)	16	39	0.68	15	58	80
Hothersall (1985)	16	-	0.66	21	-	75
Ott and Chappell (1989)	16	-	0.68	20	-	79
Fiuzat and Akerkar (1989)	20	39	0.68	20	90	89
Desai (2017)	32	39	0.60	30	90	88
Totapally and Aziz (1994)	24	39	0.68	35	90	90

The aim of this research is to investigate the possible generation of hydraulic power from sewage drain to achieve micro-scale electricity production with an energy output of less than 90 kW to overcome greenhouse gasses emission, smog formation during winter season and other environmental damages caused by conventional coal fired, LNG and oil powered power plants in Punjab province. First, a clear hydraulic energy potential for the disposal is focused on the sewage at the connecting point. Secondly, this research examines the hollow micro cross flow turbine's effectiveness and passage of foreign matter.

2. Flow duration and hydraulic potential

2.1 Local Wastewater System Outline

Several small sewage lines are connected to a waste disposal plant in Southern Punjab, Multan, Pakistan through LMQ road Sewage Line. The total sewage region amounts to approx. 46 square kilometers, the population is around 3,300,000, and the treatment capability is 7,04 x 10^5 m^3/day (as of April 1, 2015) (Khan and Badshah, 2014). The LMQ Sewerage line covers WASA-managed government sewage systems. The linked portion is called the point of attachment. In fig. 1, circular symbols illustrate the LMQ Sewerage line attachment points. The sewage pipe has an opening at the attachment points and the flow rate is measured all over the year. This research examines the flow rate at one of the attachment points to find feasible sewage hydraulic power generation.

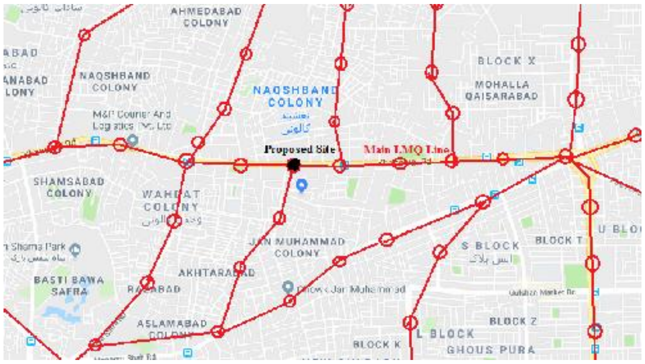


Figure 1. LMQ Sewerage Line and Proposed Site

2.2 Attachment Points Flow Duration

The daily average flow is pre-measured at the installation site to precisely calculate the energy output when a hydraulic power plant is constructed. A flow duration curve was created by arranging the daily average flow rate data provided by WASA in a descending order. Fig. 2 illustrates the flow duration curves for the planned site at the attachment points. The 97th, 187th, 277th, and 357th highest flow rates are known as the high flow, regular flow, low flow and droughty flow. In Fig. 2, Q1, Q2, Q3 and Q4 are respectively referred to these flow rates, and they are listed in Table 2. The ratio between high-and low-water discharge (Q1–Q3) and the normal water discharge Q2 (Q1–Q3)/Q2, at points of attachment, is 0.138, illustrating that the variation in the annual flow rate is low. Fig. 3 illustrate the attachment point's flow rate in which the mean, minimum, and maximum flow rates are specified for each month. The average and minimum values are almost the same and equal to the Q2.

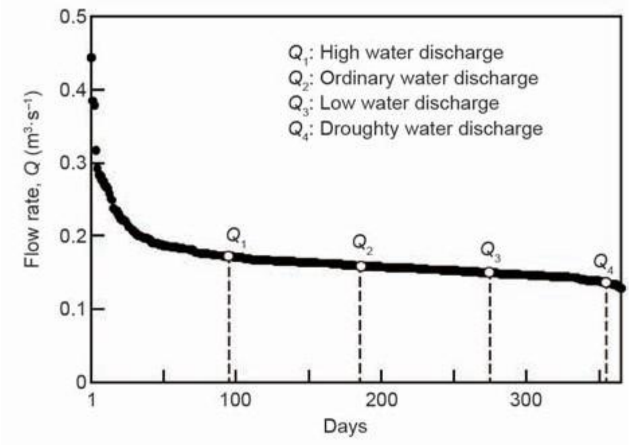


Figure 2. Flow duration at the attachment points

Table 2. Sewage flow rates

Flow Rate	**LMQ Sewerage Line ($m^{3}\cdot s^{-1}$)**
High Q_1	0.172
Ordinary Q_2	0.159
Low Q_3	0.150
Droughty Q_4	0.112

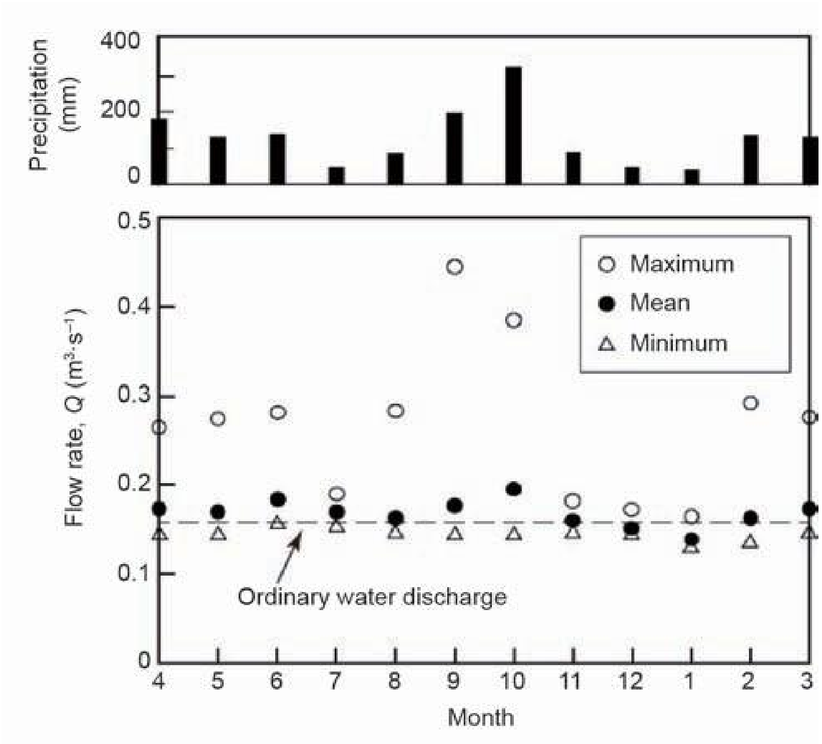


Figure 3. Monthly flow rate

2.3 Hydraulic Potential at Attachment Point

The potential of the fluid, i.e. P, flowing is expressed as:

$$P = \frac{1}{2}\,{}^{\circ}Qu^{2} \tag{1}$$

where, ρ is the fluid density and Q is the flow rate.

The velocity can be calculated from flow rate Q if the sewage is supposed to occupy 11 % of the pipe's area and velocity is calculated at the ordinary 0.159 m^3s^{-1} discharge, the hydraulic potential is estimated at 328W.

3. Design of Micro Cross Flow Turbine

The two main components of a typical CFT are the nozzle and the runner. The primary role of the system is that the overall head present is converted in kinetic energy and the water is conveyed to the blades (Sammartano *et al*., 2013).

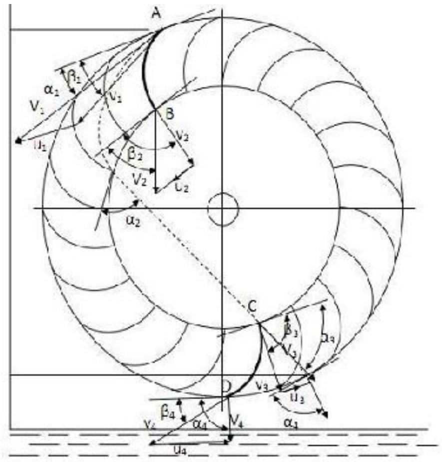


Figure 4. Path of water through turbine

As shown in Fig 4, the water enters from point A and strikes a blade AB. The water then flows across the runner's interior. The water strikes a blade CD again and passes through the exit (San and Nyi, 2018).

3.1 Shaft Design

A shaft transmits hydraulic power to mechanical power, the shaft is a rotating element of the system, generally circular in cross sections, with components like transmission gear, pulleys, flywheels, cranks, pulleys and other power supply components installed. It subjects to torque when transmitting energy at a certain rotational speed (Khan and Badshah, 2014).

3.2 Design Procedure of Cross Flow Turbine

The calculations for design involve the following steps.

Table 3. Design parameters for 290 W cross flow turbine

Parameter	Value
Generator Power (P)	196.24 W
Head (H)	2 mm
Flow Rate (Q)	0.112 m^3/s
Overall Efficiency (η_o)	68.2%

3.3 Shaft Power

The shaft power of the turbine is calculated as

$$P = ¦\,°\,gQH \tag{2}$$

3.4 Turbine Efficiency

The efficiency can be calculated as (Sinagra *et al.*, 2014)

$$¦ = \frac{1}{2} K_c^2 (1+\Psi)\cos(\sim)^2 \tag{3}$$

where, ψ = an empirical coefficient (about 0.98)
K_c = coefficient of water velocity,
(0.98 ~ 0.95)

3.5 Specific Speed

$$N_s = \frac{172.556}{H^{0.425}} \tag{4}$$

3.6 Turbine Speed

$$N = \frac{N_s \times H^{1.25}}{\sqrt{P}} \tag{5}$$

3.7 Runner Outer Diameter

Depending on the flow conditions, the runner diameter is selected. When the turbine has a higher flow, a larger turbine diameter is selected, and a lower turbine diameter is selected for the low water flow circumstances. It can be calculated as (Singh, 2012)

$$D_1 = \frac{K_u 60 K_c 2g\sqrt{H}}{\text{®}N} \tag{6}$$

3.8 Length of Runner

Runner length is calculated as:

$$L = \frac{Q}{KD_1 K_c 2g\sqrt{H}} \tag{7}$$

3.9 Radial Rim Width

The radial rim width (m) can be calculated as (Stark *et al.*, 2011):

$$a = 0.17\, D_1 \tag{8}$$

3.10 Radius of Blade Curvature

The turbine works very efficiently with the curvature of the blade. The size of the turbine varies directly with it. It is calculated as (T., 1976):

$$r_c = 0.16\, D_1 \tag{9}$$

3.11 Circle pitch of blade shape arc

The radius of circle pitch of blade shape arc is calculated as (Tiwari and Shrestha, 2017):

$$R_0 = 0.3\, D_1 \tag{10}$$

3.12 Blade Spacing

The spacing of the blade enables the water for maximum production, the distance between the blades depends on the number of blades used in the runner. It is calculated as: (Uchiyama and Morita, 2017)

$$t = \frac{KD_1}{\sin \;{}_1} \tag{11}$$

3.13 Number of Blades

The selection of the number of blades for turbine runners is very essential, fewer blades can cause the turbine to be used insufficiently and an excess number of blades can lead to pulse energy and a decrease in turbine effectiveness. It is calculated as: (Umer, 2014)

$$n = \frac{\text{®}D_1}{t} \tag{12}$$

3.14 Shaft Diameter

It should have a value to bear the load on the turbine. It is calculated as:

$$d_s = 150\sqrt[3]{\frac{P}{N}} \tag{13}$$

Using above mentioned equations, the design parameters of cross flow turbine are calculated and shown in Table 4.

Table 4. Calculated parameters turbine runner

Parameters	Symbol	Results	Unit
Blade angle	β_1	39°	-
Runner outer diameter	D_1	0.4	M
Runner length	L	0.97	M
Outer circle radius	r_1	0.152	M
Inner circle radius	r_2	0.105	M
Radius of pitch circle	R_0	0.3	M
blade curvature radius	r_c	0.125	M
Radial rim width	a	0.137	M
Number of blades	n	20	-

4. CAD Models

Several micro-turbines have been designed in the past, but presented restrictions in fabrication processes and design geometries (Mtalo *et al*., 2010). Researchers at MIT developed a planar model in order to be more compatible with existing fabrication capabilities and to ensure viability in order to compensate low head conditions in the sewerage line (Williamson *et al*., 2014). The rotor was designed using the model reported by Yang *et al*. (2009) and Nishi *et al*. (2014) but changes were made in the runner. The runner has a cavity to allow passage of waste matter and foreign material through the blades without blocking wastewater flow and eliminating the need for filtration mechanism and minimizing the cost of system.

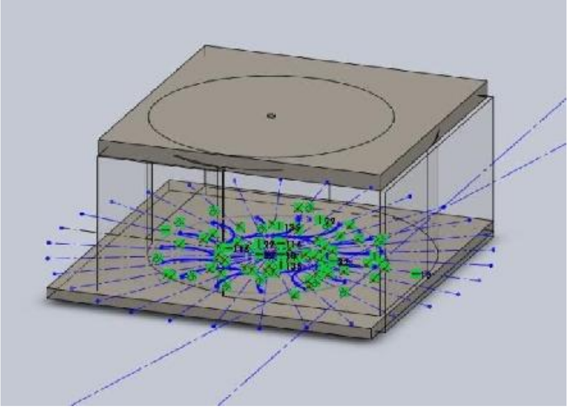


Figure 5. Rotor's Holder Design

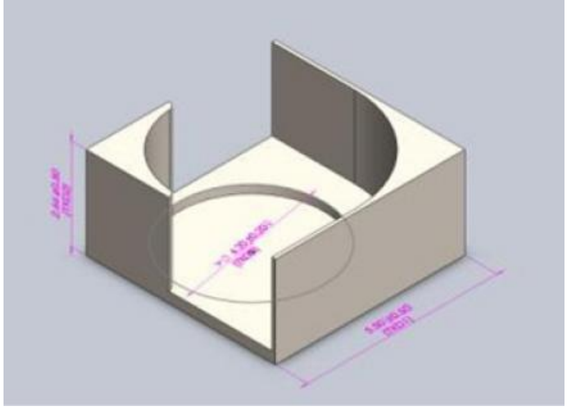


Figure 6. Holder Isometric View

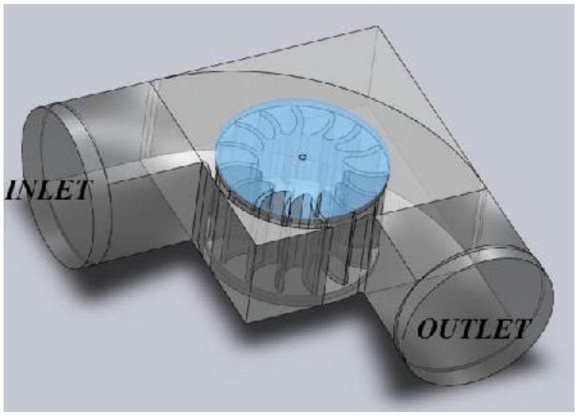
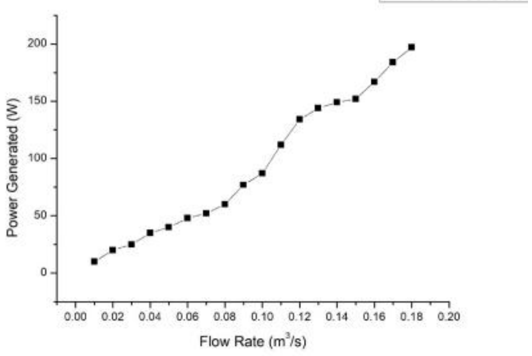


Figure 7. 3-D Assembly

5. Performance Parameters of Turbine

The design parameters are coefficient of head, coefficient of flow and coefficient of power. The performance features of the various turbine parameters are compared with each other. Both functional and non-dimensional features are traced using Origin Pro.



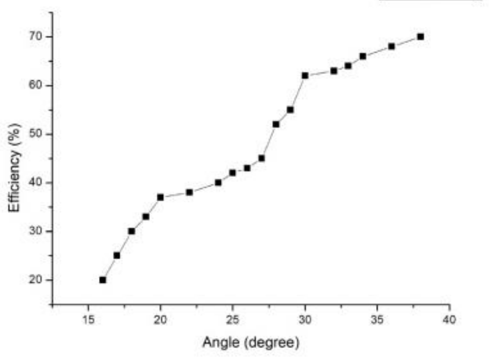


Figure 8. Performance curve between shaft power and flow rate

Figure 9. Performance curve between shaft power and effective head

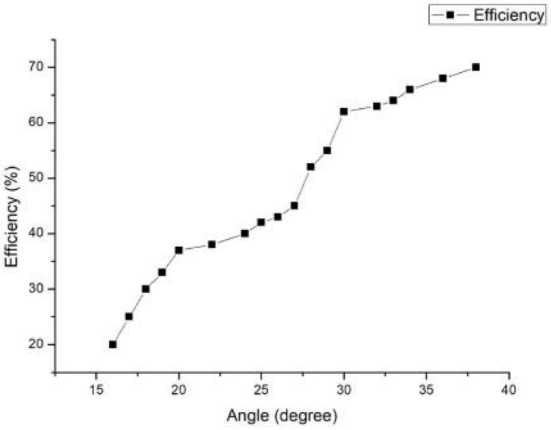


Figure 10. Performance curve between Guide Vane and Efficiency

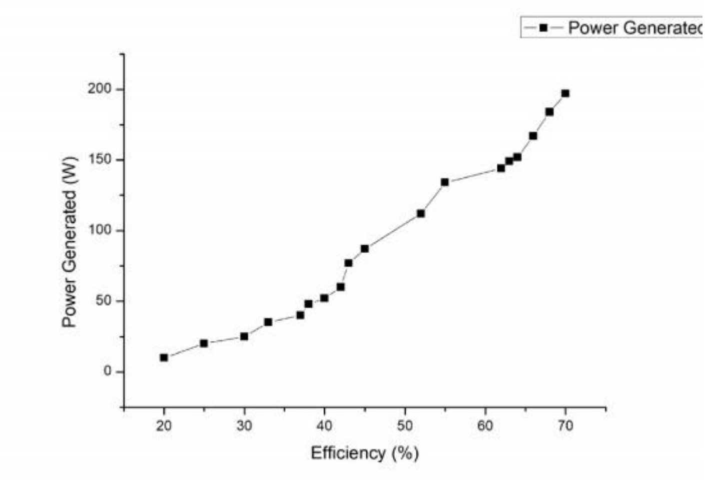


Figure 11. Performance curve between Power and Efficiency

Figure 8 illustrates a change of the shaft power with change in flow rate. As per the Figure 9 efficient shaft power and efficient heads are in direct relation, as the shaft power increases, the efficient head increases. Also, the performance curve between guide angle and efficiency is in direct relation, so increase in guide vane angle generates more power and provide facilitation of the sewage flow. The curve of efficiency and power is shown in Figure 10.

6. Conclusions

The flow duration at the location of the LMQ road sewage line was inspected and the potential of the sewage for electricity production was estimated to search for potential micro cross flow turbine installation in the sewage. The study shows that the attachment point has enough hydraulic potential to be used during the whole year. An installation of a crossflow turbine on the attachment point was examined considering the effectiveness and waste-matter passage through micro cross flow turbine. The investigation shows that the fiber attachment to the micro cross flow turbine is suppressed by a runner with rounded blades and guide vane with tapered blades, thus increasing Turbine Efficiency. It was therefore observed that micro crossflow turbine could be used to generate enough electricity from sewage flow in pipes.

Nomenclature

a	Radial Rim Width	α	Angle of Attack
β	Blade Angle	CFD	Computational Fluid Dynamics
d_s	Shaft Diameter	D_1	Outer Diameter
ρ	Density of Water	η_o	Overall Efficiency
Ψ	Empirical Coefficient	g	Gravity
H	Head	K_c	Coefficient of Water Velocity
K_u	Coefficient of Velocity	L	Length of Runner
MCFT	Micro Cross Flow Turbine	N	Number of Blades
N	Turbine Speed	N_s	Specific Speed
P	Power Generated	Q_1	High flow rate
Q_2	Ordinary flow rate	Q_3	Low flow rate
Q_4	Drought flow rate	Q	Average flow rate
r_1	Outer Circle Radius	r_2	Inner Circle Radius
r_c	Blade Curvature Radius	R_o	Radius of Circle Pitch of Blade
t	Blade Spacing	u	Water Velocity
WASA	Water and Sanitation Authority		

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