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Design and Analysis of In-Line Turbine for Micro-Hydropower Plant

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Abstract

Energy in different forms plays a key role in daily life. Electricity is one such form of energy. The fact that fossil fuels are depleting at an alarming rate, there is a need for alternative sources of energy. Hydropower is one of the important renewable energy sources and popular because of its advantages. The micro hydropower plant is one of the best solutions for energy crises. The micro hydropower plant can be operated with various streams, even in sewage treatment plants. The project aims to generate electricity from treated water of sewage treatment plant using an inline turbine. In the present work,the inline turbine is designed, which can be used to harness power from this water which otherwise is discharged into the river. The turbine selected is the Kaplan turbine. The expected efficiency was assumed to be 90%. Initially,the theoretical design was performed for determining the main characteristics which resulted in 90.17% efficiency. Theoretical design is approximate and has to be confirmed by Computational Fluid Dynamics (CFD) which resulted in 85.76% efficiency. Static analysis is also performed to know the effect of working conditions through simulation. This methodology can be used at various water sources which can provide energy for general utilization at that site.

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Keywords— *Energy, Hydropower, Micro Hydro Power Plant, Sewage Treatment Plant, Inline turbine, Kaplan turbine, Efficiency, Computational Fluid Dynamics*

I. INTRODUCTION

Energy is an essential part of our daily lives! We use various forms of energy in our daily work routine. One of these is electricity. The economic development of any country is often closely linked to its consumption of energy. India ranks sixth in the world for total energy consumption. But due to its population, the power demand is very high and is growing steadily. Knowing the dreadful fact that non-renewable sources will eventually deplete, the importance of renewable sources has been increased. Renewable energy is the need of the hour. These are infinite and hygienic sources of energy. Amongst these, hydropower is a clean and renewable energy source that provides affordable power throughout the country.

The hydropower plants are generally classified based on their electricity-producing capacity. One of them is Micro-hydro which typically produces from 5kW to 100kW of electricity. Knowing the reliability and advantages, the Ministry of New and Renewable Energy (MNRE) is encouraging the development of small hydro projects both in the public as well as the private sector. The estimated potential of about 20,000 MW of small hydropower projects exists in India. A target of adding about 5000 MW by 2022 is kept by the Ministry of New & Renewable Energy by SHPs [18]. Hence micro-hydropower plants can be reliable for the generation of energy from small streams and even sewage treatment plants.

A Sewage micro hydropower system can be reliable and provide stable, economical electrical energy micro-hydropower systems using wastewater from the community [14]. One of the largest consumers of electricity is Sewage Treatment Plants (STP). Hence it will be advantageous to generate the electricity from sewage system and use it for plants so that the electricity consumption can be reduced.

The large quantity of flowing water inside the pipeline can generate safe power. But the problem of using this hydropower is to select a water turbine which is suitable for pipeline conditions. The in-line turbine is a new concept that can be adopted due to its advantages such as economy, less space, less maintenance, etc[15, 6].

The selection of a turbine for a site can be determined by the following figure 1[5].

Working Principle: The turbine can be installed in pipes for a micro hydropower plant. The water flowsa certain head through the pipe. The running water moves the turbine, the turbine spins a generator and electricity is produced.

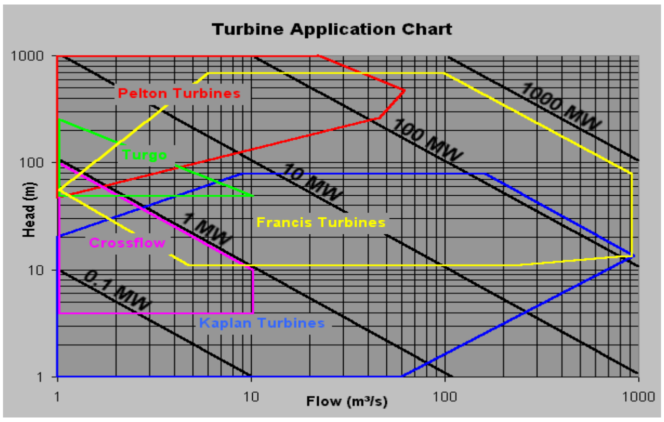

Fig. 1. **Turbine application chart**

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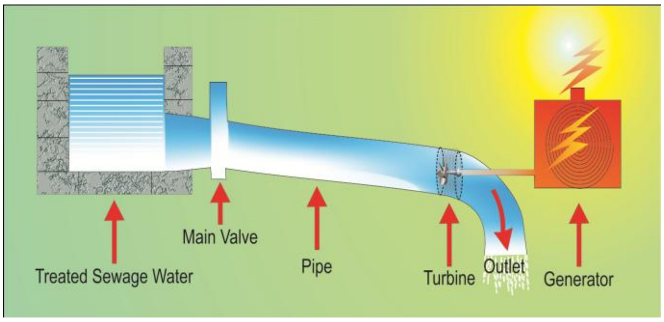

Fig. 2. **Flow diagram for the micro hydropower plant at stp**

II.LITERATURE REVIEW

A literature survey reveals that various researchers have studied the behavior of water and use it to harness power by using the turbine.

Karan Bhandari, OjasPravinRahate highlights how Micro Hydro Power Plant (MHPP) can be used to partly meet the high demands of electricity. The authors had selected a turbine and performed calculations. The designed turbine resulted to produce 73,355 units annually with a benefit-cost ratio of 9.53 and a payback period of 1.5 years [5]. The concept of the alternative energy source of municipal wastewater for micro-hydropower generation is described by ArchanaTamarkar, S.K.Pandey, S.C.Dubey in their Research paper [14]. In 2016 Uchiyama, Honda, Okayama, and Degwa made a Hollowed pico-hydraulic turbine and observed its feasibility. The experiment was done by the connecting turbine at the outlet of sewage pipe in Japan. They observed that connection points have the potential that can generate power all over the year, Hence concluded that pico-hydraulic turbine can use at sewage flow pipe [16]. A paper by ChamilAbeykoon, Tobi Hantsch presents a thorough design of the Kaplan turbine and presented its CFD analysis. They analyzed and optimized the blade using CFD and get 93.01% efficiency. They also observed that turbine angles influence power output [1].

III.DESIGN OF TURBINE

For getting the expected output, the selection of a turbine is important. It depends on discharge and head. As on sewage treatment plant head and discharge both are low, hence by referring the figure 1, Propeller / Kaplan turbine has been selected.The design is as in[8], [1]. A case study is considered where –

Q = 130 MLD = 1.5 m^3/s

Diameter of pipe = 457.2 mm

H = 1.0 m ρ = 1000 kg/m^3 g = 9.81 m/s^2

Assume Hydraulic Efficiency = η_h = 90 %

Further, calculations were done to find the characteristics of the blade for the runner as shown in table 1. Rotational speed comes out to be 600 rpm. Runner diameter is D_e = 0.4m and hub diameter is $D_i = 0.12\ m$.The numbers of blade (z) selected is 4.

$$P_{water} = \rho . g . Q . H = 1000 \text{ x } 9.81 \text{ x } 1.0 \text{ x } 1.5 = 14715 \text{ W}$$

$$P_{runner} = \rho * \frac{\pi}{4}\left(D_e{}^2 - D_i{}^2\right) * w_m * u * \Delta w_u$$

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$$P_{runner} = 1000 * \frac{\pi}{4}(0.4^2 - 0.12^2) * 13.15 * 8.17 * 1.08 = 13268.53 \text{ W}$$

Now the theoretical efficiency is given by:

$$\eta_r = \frac{P_{runner}}{P_{water}} * 100 = 90.17 \%$$

TABLE I. CHARACHTERSTICS OF THE BLADE

d	0.4	0.33	0.26	0.19	0.12
u	12.56	10.36	8.17	5.969	3.769
c_{u1}	0.64	0.786	0.99	1.36	2.16
c_{u2}	0.75	0.918	1.165	1.59	2.525
w_{u1}	-11.92	-9.574	-7.18	-4.609	-1.609
w_{u2}	-11.81	-9.442	-7.005	-4.379	-1.244
$w_{u\infty}$	-11.865	-9.508	-7.092	-4.494	-1.426
w_m	13.15	13.15	13.15	13.15	13.15
w_1	17.75	16.26	14.98	13.93	13.25
w_2	17.76	16.18	14.89	13.86	13.20
w_∞	17.71	16.23	14.94	13.89	13.22
β_∞	132°	125.86°	118.34°	108.87°	96.19°
$180° - \beta_\infty$	48°	54.14°	61.66°	71.13°	83.81°

IV. ANALYSIS OF TURBINE

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows. It is generally used for analysis and simulations of systems involving fluids. As the experimental methods are costly, times consuming, and difficult to install, CFD is a cost-effective tool that provides results in computer systems without loss of money and time. To perform analysis ANSYS software is used. In ANSYS, Fluent module was selected. It consists of 5 steps for completion of the project.

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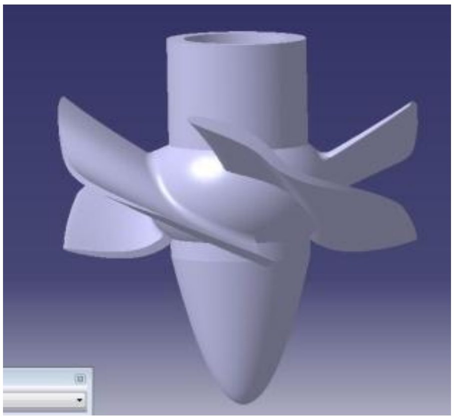

Fig. 3. **CAD model**

A. Geometry

The first step is modeling (CAD) of the object which is to be analyzed. In the present work Runner of a Kaplan turbine is designed using CATIA V5 software. Then it was imported in ANSYS 2019 as .stp extension file. Figure 3 shows the image of the model used in this study.

B. Meshing

Meshing is a process of dividing the given geometry into a small number of parts known as elements. The analysis is performed on every element and nodes which provide overall outputs. Following figure 4 illustrates a meshed model of the turbine used.

The geometry has meshed with tetrahedral cells of pentagonal shape and the equation selected was the linear equation. Further names for edges and faces were given for its easy identification when the model is opened in the solver. Inlet of water to the runner is named “inlet”, water leaving the runner is named “outlet”, the runner is named “rotor” which is a rotating portion and the pipe is named “stator” which is a static portion.

C. Setup

In this step, the meshed geometry is launched in FLUENT.This step involves giving input to all required data.The various parameters provided as input data are in the following table 2.

D. Solution

The solver works iteratively. Hence parameters were initialized with 50 iterations. The residual shows when the residual values have reached the specified tolerance, the tolerance in this model was set to 10^{-5}. A hybrid equation was used to start calculations. After providing data and setting, the calculations are run, which starts with iteration and stops when all points converge.

E. Results

Variations of velocity streamline patterns in the runner are as shown in figure 5. It is observed that the velocity inside runner increases from its inlet to outlet and hence velocity is maximum after the blades of the runner. The maximum velocity observed is 70.33 m/sec and a minimum velocity 0 at the pipe wall. The velocity is zero at the pipe wall because there is the friction of water and pipe which reduces the speed of the flow.

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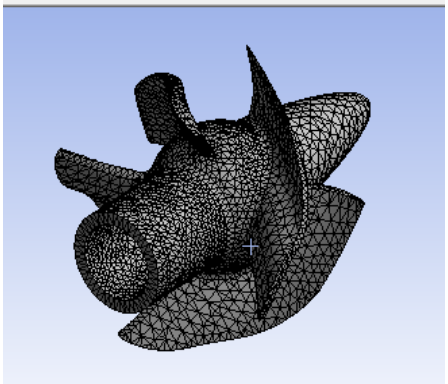

Fig. 4. **Meshing**

Pressure contours/distribution are also shown in figure 6. The pressure inside runner decreases from its inlet to outlet which is just because the pressure energy is being converted into mechanical energy. Maximum pressure occurs at the inlet of the turbine. The maximum pressure in the pipe is 6.216×10^5 Pa and the minimum is -2.707×10^6 Pa.

Static analysis was also done with given loading conditions. The maximum pressure observed on the turbine is 5.609×10^5 Pa and the minimum is $- 2.957 \times 10^6$ Pa. Maximum pressure occurs at the starting of the runner which gets reduced further. It is observed in figure 7, that at some portion of blades the pressure is lesser than the vapor pressure assumed in the design. Hence there is a little risk of cavitations which is a common problem in hydraulic machines.

TABLE II. SETUP CONDITIONS

Internal flow	Turbine (fixed in line with the pipe)
Working fluid	Water
Type of flow	Laminar
Model	k-epsilon equations
Fluid material	Water
Model material	Stainless steel
Cell Zone Conditions	
The rotor zone	The region of the model (turbine) that will rotate the Rotor speed of 600 rpm.
The stator zone	The remainder of the model excluding the runner i.e. pipe. Stator wall with no shear stress.
Boundary Conditions	
Primary variable	Pressure

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At inlet	Flow is assumed to be fully developed. the velocity of water 9.2 m/s.
At outlet	The pressure was set to atmospheric pressure.
The solver time	Set to steady, as the flow is assumed not to change with time.

The maximum stress (equivalent / Von-Mises stress) on the runner is 0.0011139 MPa while the ultimate tensile strength of the runner material (stainless steel) is around 830 MPa. Hence the factor of safety is 745 x 10^3 which is so high. Hence the runner will work safely at this stress. The stress developed at the runner blades is maximum at joints between the hub and runner blade.

The maximum displacement (total deformation) in the runner is 1.0024 x 10^{-5} mm at the edges of the blades. The blades behave like a fixed beam and show no failure during the analysis.

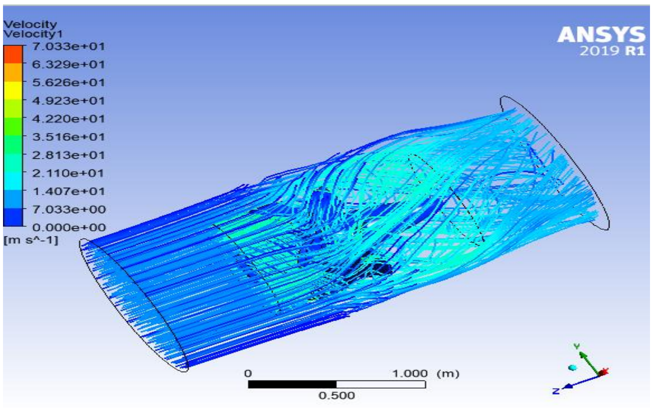

Fig. 5. Velocity streamline pattern

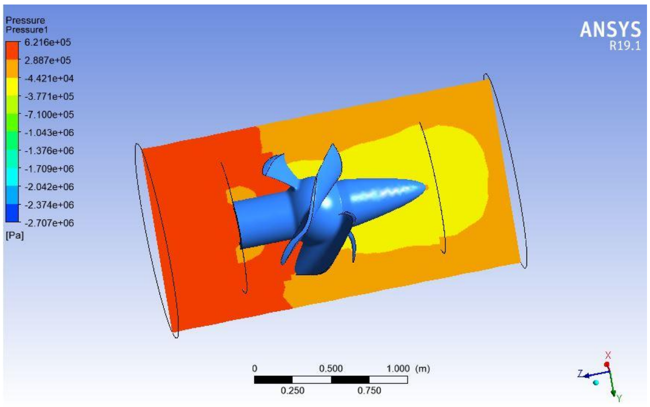

Fig. 6. Pressure distribution inside pipe

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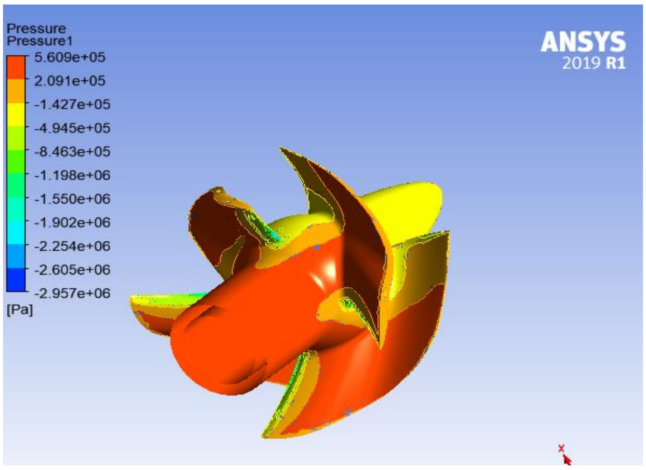

Fig. 7. Pressure on the turbine

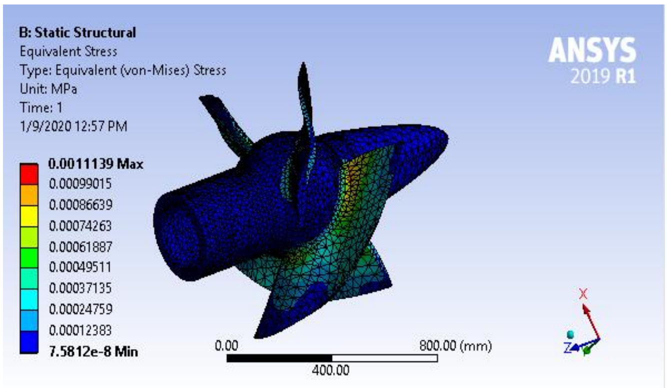

Fig. 8. Equivalent (Von- Mises) stress

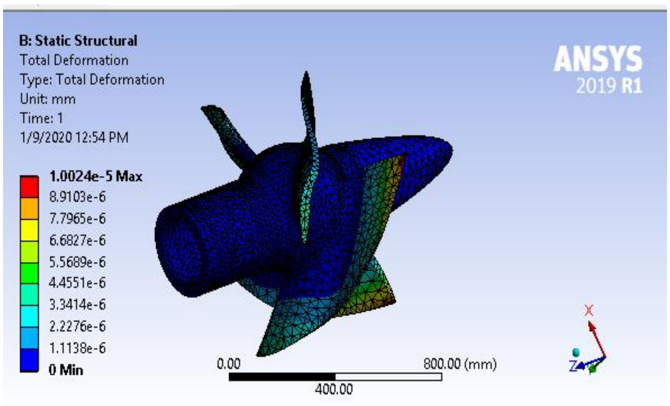

Fig. 9. Total deformation

Along with these analyses torque was found for calculating power. It comes out to be 200.963 N.m.

$$\tau = 200.963\ N.m$$

$$P_{water} = \rho.g.Q.H = 14715\ \text{W}$$

$$P_{runner} = \frac{2\,\pi\,N\,\tau}{60} = \frac{2\,\pi\ \times 600\ \times 200.963}{60} = 12620.47\ W$$

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$$\eta_r = \frac{P_{runner}}{P_{water}} * 100 = 85.76\ \%$$

V.CONCLUSIONS

The efficiency obtained from theoretical design is 90.17 % while on the software it is 85.76 %. Hence the results obtained from flow simulation are found to be by turbine efficiency assumed i.e. 90%. The pressure difference which is created under the conditions stated in this case is enough to create the required torque on blades and to get assumed efficiency.

The results show that the stresses produced under static load are less than the ultimate tensile strength. Also, pressure observed on the runner and total deformation at blades are less. Hence the blade profile shape is safe enough and the turbine model is statically stable against boundary conditions.

The generation of electricity from treated water of STP by an in-line turbine can be used for the plant itself or use for other appliances in the premises of the plant. This is a safe and promising technology and this same principle can be used at various water sources.

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