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Parametric Optimization of Gravitational Vortex Turbine in the context of Upper Punjab of Pakistan

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***Abstract*-Energy requirements are growing rapidly with population growth and industrial expansion in Pakistan. It is difficult to meet the energy demands using fuel and gas for power generation due to the rapid increase in the fuel prices. Pakistan is blessed with an incredible hydel potential but only 15% of the hydroelectric potential has been harnessed. The country can meet its ever-increasing demand for electricity in a cost-effective way, if the remaining potential is utilized effectively. Four rivers of Punjab namely Sutlej, Ravi, Chenab, Jhelum join the mighty Indus at Mithan Kot which ultimately falls into the Arabian Sea. Punjab has the distinction slope for ideal gravity flow in Pakistan. After the Indus Water Treaty in 1960, large number of link canals were constructed and can be used for power generation in addition to irrigate the lands for the growth of agriculture in Punjab. The current research work aims at the development of Pico hydro turbine with gravitational vortex for the sites in Punjab where the water flow rates in the canals are in the range of 0.005-0.01 m^3/sec and available head is 1.5 m. This turbine has been selected based on the availability of specific speed of 71 according to the site data. Numerical simulation was used for the design and optimization of basin, blades and rotor for the turbine. The simulation was accomplished for a range of notch angles and its optimum value was found to be 153^0 for the substantial increase in the water velocity for improved power output. It was revealed that the proposed design of steel structure should be replaced with reinforced concrete structure for the flooding condition where the flow rate is 0.2 m^3/s. The proposed design for flooding conditions has an optimum thickness of 150 mm for the wall and the base and the transverse reinforcement is 0.27mm^2/mm.**

***Index Terms*-- Hydel Power, Pico hydro Turbine, Gravitational vortex, low head turbine, flow rate in Pakistan, electrification.**

I. INTRODUCTION

The under developed areas of Pakistan lack in electricity and this deficiency is major obstacle in the socio-economic growth for its prosperity. The demand of electricity in Pakistan right now is 15,000 MW, which will rise up to 50,000 MW in upcoming 30 years. The energy demand in Pakistan is increasing at the rate of 11-13% per year. The conventional methods used in Pakistan aren't enough to meet these demands [1].

According to the survey, more than 60,000 MW of hydroelectric sources have been identified in Pakistan but only 10-11% of them are brought into the use which only generates near about 7228 MW of electricity. If The shortfall is recovered through the import of the crude oil, it consumes 20% of foreign reserves of the country.[1] The solution to this problem lies in the development and construction of hydropower resources along the sides of the rivers and canals in Pakistan. The current energy crisis in Pakistan can be resolved through the development of small hydro power plants. Dams are very expensive to build as they require a suitable site with substantial acquisition of land and huge resources for the development and maintenance. Small hydro power plants are of various types are easy to develop and maintain for small local community and depend upon their physical requirements. One such type is Vortex turbine but its commercial use is limited for the production of electricity in Pakistan. Most of the villages in the remote areas of Pakistan have lakes and rivers passing nearby them. There is either very limited supply of electricity or no electricity for the residents of these villages. Vortex turbine is the best solution to these problems. This turbine requires a very low head, which means that it can be developed at small rivers and lakes The water wheel require a high head and cannot be installed at every lake or river.

A study was carried out in region of Terai Nepal to evaluate the performance of turbine.[2] The comparison in the first phase disclosed that the turbine with less number of blades and smaller radius is more efficient.[3] Conical basin provided the maximum efficiency of 26.63%, which was significantly greater than the efficiency of the cylindrical basin. Some studies focus on the sustainability and increase in the health of water bodies by utilizing Gravitational Vortex Power to generate electricity.[4-6] Free Surface Vortex (FSV) has been discussed from both power and flow points of view along with a suitable turbine system.[5] The efforts have been made to improve the efficiency of Gravitational

Water Vortex Power Plant by optimizing the conical basin shape for an efficient basin design. Notch angle, canal height, notch inlet width, and cone angle were the altered design parameters. Maximum efficiency of 74.35% was obtained by using large runner at the lowest most position [7].

Few studies show that GVT is capable of generating electricity from heads varying from 0.7 m to 3 m [8]. The general recommendations has been made by researchers for the various parts of the water turbine material [9, 10]. A comparison of steel structure with concrete structure and the recommendations for the reinforcement has not been made and this provide the gap for current research. Commercial CFD code was used to explore the best configuration of the vortex pool system. Experimental results were compared with the CFD results which proved that ANSYS Fluent is an authentic modeler. The system proved to be 40% efficient. [11] focused on the effect of introducing baffle plates on the propellers. [12] It was found that the increase in blade size and increasing surface of the blades gave low turbine speeds but gave maximum efficiency and high output of turbine power. [13] Under head of 0.5m Cross flow blades were found to be most efficient in generating maximum output of electricity which was 68.4%. [14] Countries having potential to produce electric power out of water resources having less than 3m of hydraulic head and a water flow rate of 0.5 m/s or greater, are not paying head towards this renewable source of power generation.

Ghani[15] used Euler Turbomachinery Equation and proved that the circulation force of the water vortex was one of the dominant factors as compared to the others while considering the rotational speed of the turbine. Flat blades showed 21.6% efficiency at 3.27 rad/s whereas curved blades showed 22.2% efficiency at 3.56 rad/s. [13] The researcher worked on number of blades and shape of blades. This resulted in the improvement of the turbine efficiency from 30% to 50%.[15][16] Rahman focused on the effect of the number of turbine blades and turbine baffle plates on the efficiency of the gravitational water vortex turbine.[17][18] The water flow rate used throughout was 0.004-0.006 m^3/s. The experiments showed that 50% baffling plates covering both top and bottom showed the maximum efficiency. The efficiency under that condition was 43.83% which was 6.5% higher with no baffle plates. [19] Ghani described that the maximum efficiency of 43% obtained was at 0.7m of head with a flow rate of 500 l/s. The power generated was 2.45 kW.[15]. Dhakal did experimental analysis by varying the positions of the runner. The comparison of the results verified that the maximum efficiency was obtained by placing the turbine in the bottommost position from the top of the conical basin. [5, 20] The study highlights the gaps in the existing progress of the Gravitational Vortex Hydro Turbine. [19] A study was made to see the effects of the design of runner on the performance of Gravitational Water Vortex Turbine (GWVT) with a conical shaped basin. [21] The study showed that runner has a great impact on the structural strength of the turbine.

The comparison of steel structure with concrete structure and the recommendations for the reinforcement has not been made by the researcher and this provide the gap for current research. The performance and the supreme shape of the blades and basin of Gravitational Vortex Hydro Turbine is analyzed in this research. The research aimed to determine the feasibility of this project in Pakistan with the available head of 1.5m and flow rate of 0.005-0.01 m^3/sec which was done by two methods including ANSYS Fluent simulations and fabrication of prototype based on the results of the simulation for testing and analysis purposes. The innovation in the design under this study included the addition of a hybrid blade to control the inlet flow and keep the turbine working at controlled conditions. Both numerical and experimental studies have been performed. Different speeds have been tested and studied by varying the parameters to obtain effective results. Two materials i-e steel and concrete are analyzed as a runner material and it is proposed that the circular part of the runner is facing high impact loads and under flooding conditions to save the design a reinforcement of 0.27 mm^2/mm will be required. After ANSYS analysis it is predicted that the steel blade may fracture due to load at certain points. It is recommended that instead of welding which is used during prototype manufacturing some other method such as 3 d printing should be used.

II. METHODOLOGY

A. SELECTION OF TURBINE BASED ON THE SITE

Site survey and evaluation is carried out considering multiple factors such as, areas where water is abundance with head of 1-2 m and considerably low flow rates, but electricity is short or not available. Total head 'Hg' between point of fluid water outlet and inlet points of turbine by using spirit level and plank is calculated by the following formula as equation (1).

$$\boldsymbol{Hg = h1 + h2 + h3 + \cdots \ldots\ldots + h\,n} \qquad \textbf{(1)}$$

By Determining area cross section by equation (2) measuring width b (m) and height h (m) of the available site.

$$\boldsymbol{A = b * h} \qquad \textbf{(2)}$$

Then when we want to find velocity V (m/s) measure the time t (sec) it takes for a float to travel the length 'L'.

$$\boldsymbol{V = L/t} \qquad \textbf{(3)}$$

Hence the flow can be found by multiplying 'V' with cross section area 'A'.

$$\boldsymbol{Q = V * A} \qquad \textbf{(4)}$$

The choice of the speed (N) depends on the speed of the generator and type of the drive used. The optimum range of rpm rang of 160-200 that is why we are selecting rpm of 185. At this rpm to calculate specific speed we use the following equation. [22]

$$\boldsymbol{nq = \frac{n\sqrt{Q}}{H^{0.75}}} \qquad \textbf{(5)}$$

The specific speed extending from 70<nq<300 is for Pico hydro turbine. [23] By calculating all these parameters, specific speed lies in range of efficient low head GVT.

B. FLOW VELOCITIES CALCULATIONS FOR THE BLADE

The angle of attack of the blade profile is $\alpha 1$, 16° and $\alpha 2$ the angle of flow leaving the conical basin is 90°. The radial velocity component Vr of the flow is zero because only the tangential component Vt takes part in the vortex generation having magnitude of 0.4 m/s. The value of the tangential component based on the vortex strength of 0.133 m2/sec has been calculated. The absolute inlet (V1) and outlet velocities (V2) calculated as 5.91 m/s and 1.629 m/s respectively. Similarly, Inlet (U1) and outlet (U2) Wall velocities are 0.314m/sec and 1.41m/sec respectively. The inlet Vf1 and outlet Vf2 flow velocities are same with a magnitude of 1.629m/sec. The resulting relative velocities of flow w.r.t blade are Vr1 and Vr2 having magnitude of 1.565m/sec and 3.087m/sec respectively.

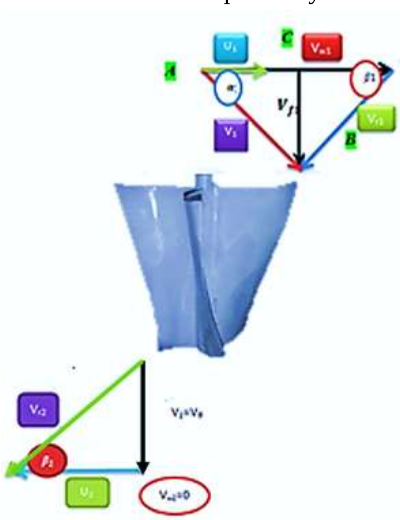

FIGURE 1. Velocity Diagram of Blades

To design the runner stainless steel sheet 20 gauge (thickness: 0.911mm) has been used. The notch angle was designed at 153 degrees, 90-degree bend on the both side of the runner using bending machine rather than welding sides in order to construct a smooth runner with minimal losses possible.

TABLE 3.1
RUNNER CHARACTERISTICS

Runner Parameters	**Optimized value(m)**
Sides Height	0.20
Length	1
Inlet Width	0.25
Outlet Width	0.14

After thorough study of past research and literature review, we came to the conclusion that the shape that is most efficient for vortex generation and overall power production is the designed conical shape at an angle of the basin having a cone angle between 60° to 70°. For this purpose, selection of a 2.7m inlet diameter of the basin, and following the 14 to 18 % ratio of Inlet to Outlet Diameter for optimized results. [24] we used a 6 cm outlet diameter whereas if a greater variation in runner position and diameter is brought in design it can result in deformed vortex results and non-uniform visible characteristics. The best suggested conical angle ranges from 60° to 70°, so we derived 64.64° degree cone angle for the conical basin for better vortex and momentum transfer to turbine blades for better output.

In reference to past literature the curved blade profile was found to be the most efficient turbine blade with efficiency at 82% rather than straight profile (46%) or twisted profiles (63%). We have developed a hybrid blade design that was curved as well as slightly twisted which would ideally help in generating and keeping vortex formation in water flow consistent and much efficient than the prior designs put to test.

TABLE 3.2
CONICAL BASIN PARAMETERS

Basin Parameter	Optimized Value (m)
Basin Height	0.45
Inlet Diameter	0.27
Outlet Diameter	0.06
Inlet Width	0.135
Cone Length	0.24892
Cone Angle	$\boldsymbol{Tan-1\ (0.24892/0.135)\ =\ 64.64°}$

The Number of blades was decided to be four after considering size average of turbine and results from research where the author claimed the efficiency of a turbine would eventually be more [12] The blades were made of steel itself for maximum durability, strength and ease of fabrication. The curved and twisted profile was given with the help of bending mold machine which had one corner fixed of thee precut design and bended to desired shape from different sides. The formulations attached.

Radius of Curvature of Blade $R = \frac{[OD^2 - ID^2]}{[2*OD*\cos\beta 1]}$ **(6)**

$$= \frac{[0.27^2 - 0.06^2]}{[2*0.27*\cos 24.96]} = \mathbf{14mm}$$

TABLE 3.3
GWVTPP Blade PARAMETERS

Basin Parameter	Optimized Value (m)
Blade Upper side length	0.09906
Blade Lower side length	0.04826
Blade Mid-section length	0.07366
Total longitudinal length	0.1778
Total Cross length ratio (upper to lower)	0.1524:0.0762 (2:1)
Blade Upper side length	0.09906

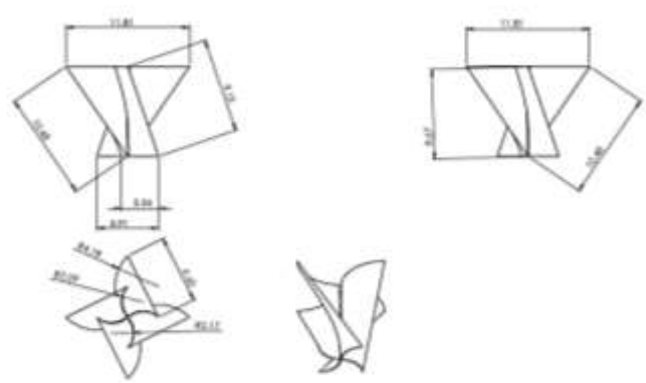

FIGURE 2. GWVTPP Blade Design

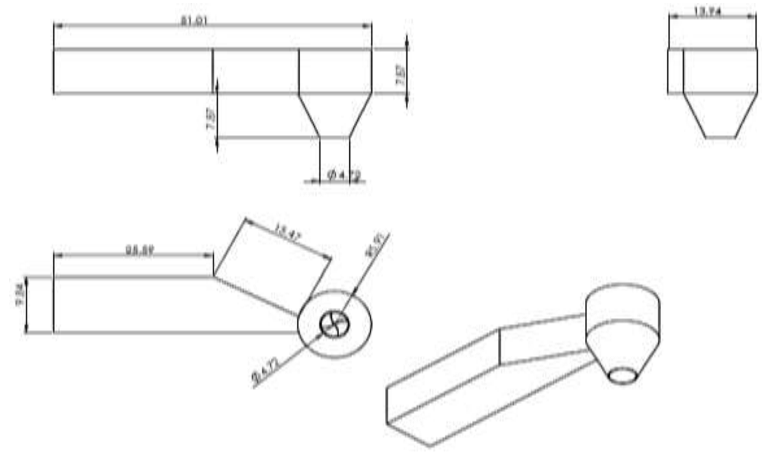

FIGURE 2. GWVTPP Turbine Design all dimensions in cm

A vortex is created in the passage of water that create a whirl is shown in Figure 3. This whirl rotates the shaft which in turns produce the power for the given gross head of 1.5m. Here for a power output of 0.30.5kW the expected vortex design should have a, b, c, d, e, f, g and h are 22, 19.6, 16.8, 11.2, 8.4, 5.6, 2.8cm respectively. [5]

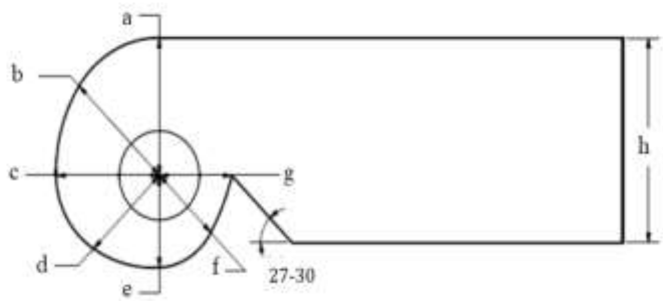

FIGURE 4. Pico-hydro standards for open spiral volute or vortex

This model is designed to work on a low head of 1.5m and flow rates of 0.1m3/sec having conical basin due to which it creates a vortex line, which provides the driving power to the turbine. The turbine will be tested in real practical site for determining the power outputs, efficiency, and optimum design parameters results etc. The blade shown in figure is made of 18-gauge steel.

FIGURE 5. GVT top view

The flow rates during experimentation were about 0.1m3/sec measured using the flow method as described earlier. Power Input is 1.4kW at this particular flow rate and head overall flow rate was varying. The Power Output at multiple flow rates was measured using a Clamp Multi-meter by applying the load of Bulbs being attached in series where Power output was estimated via the product of voltage and current drawn by the circuit, which was in turn utilized to determine the torque from the following formula. Power Output: V*I watt. Then the efficiency can be calculated by taking the ratio of Power output to Power input and multiply it by 100 to get a percentage value.

FIGURE 6. Gravitational Vortex Turbines Side View

For cost effective manufacturing we choose steel sheet of 16 gauge. With the help of cold forging process, we mold that sheet into our required design

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C. CFD ANALYSIS AND METHODS

Three-dimensional Analysis of GWVTPP has been performed on ANSYS CFX 16.1 (ANSYS Inc.). In order to find the behavior of working fluids air and water, the inlet and outlet pressures were considered 101,32Pa. The water flow is assumed steady flow with no slip conditions. The water is considered to be viscous, incompressible with density of 998.2 kg/m3 and viscosity of 0.001003kg/m-s (at room temperature 25ºC) and Newtonian. The vortex turbulent flow generation depends upon cylindrical continuity of the profile while considering water vortex as flow patterns with streamlines having concentric circles. The turbulent model was assumed in order to investigate the flow pattern of the system. The initial mean velocity of fluid flow for analysis is set to be 0.1 m/s and the fluid was flowing through the area having hydraulic diameter of 0.2727 m.

For Analysis, the velocity is uniform along the length of the runner, with which the water strikes the runner. The flow in the water vortex should be considered in viscid and ir-rotational because of the negligible viscosity. The wall of the fluid flow domain was presumed stainless steel and with no slips conditions. The GVT Turbine 3D including channel, blades and basin is shown in Figure 8.

The outlet was pressure outlet. The head and pressure losses should be kept negligible. The meshed geometry is shown in Figure 9. The mesh contains 80383 number of nodes and 294997 elements with a combination of Tetrahedral, Hexahedral and wedges geometries.

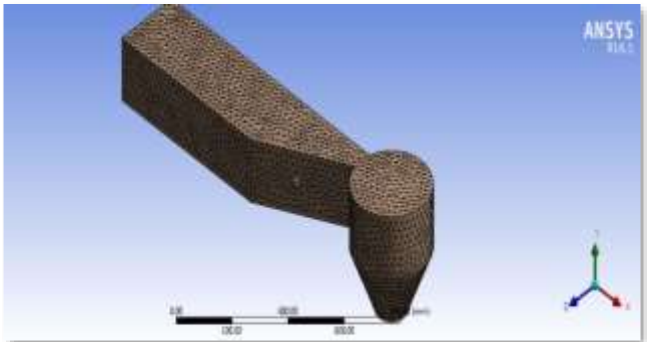

FIGURE 7. Meshed geometries of a 3D model of Turbine

D. MODIFICATION FOR FLOODING CONDITIONS

A RCC structure model of the GVT inlet was developed on STAAD to ensure a safe and economical water channel as shown in Figure (8). The input data included a head of 1.5m and a discharge of 0.2 m^3/s. It was assumed that under flooding conditions the mass flow increases this much. Wind load was considered along with the water pressure and self-weight of the structure during the analysis. The purpose of this simulation is to make this structure safer under flooding conditions. This will suggest the reinforcement requirements of concrete structure as well as it also ensures the safety under the above-mentioned volumetric flow rate.

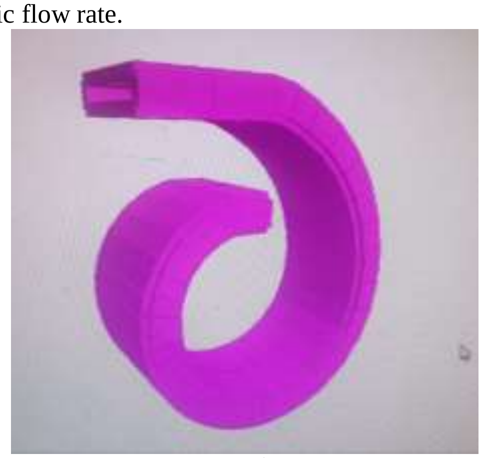

FIGURE. 8. 3D Model of RCC Water channel

III. RESULTS AND SIMULATION

A. EXPERIMENTAL RESULTS

Experimentation has been done under constant head and varying flow rates as describe earlier. The resultant power obtained is enough for the electrification of a community of 8-12 houses of rural areas. The efficiency of the turbine increases when there are better flow rates.

TABLE 4.1
EXPERIMENTAL RESULTS OF OUTPUT POWER AND EFFECIENCY

	Power Input			Power Output			Efficiency
Sr #	H (m)	Q m3/sec	Pin (W)	V (V)	I (A)	Pout (W)	η
1	1.5	0.065	952	24	25	809.2	65
2	1.5	0.085	1245	24	35.2	846.6	68
3	1.5	0.094	1377	24	38.73	929.47	67.5
4	1.5	0.099	1450	24	42.29	1015	70
5	1.5	0.101	1480	24	44	1053.76	71.2

B. NUMERICAL SIMULATION

After application of the boundary conditions on the designed blade model the velocity distribution on the blade profile is determines as shown in Figure 9. In Figure 10 the velocity contour of the complete channel with dimensional parameters as in the model and notch angle of 153º is given. In Figure 10 and 11 respectively, the pressure contour of the blade profiles and the channel are shown. The pressure contour portrays the resulting force distribution due to fluid momentum with which it strikes the blades and causes it to rotate and generate electrical energy. In Figure 12 the Kinetic energy impact contour is shown and in Figure 13 the streamline velocity flow behavior of fluid is shown and the effect of geometrical parameters on the fluid velocity are described.

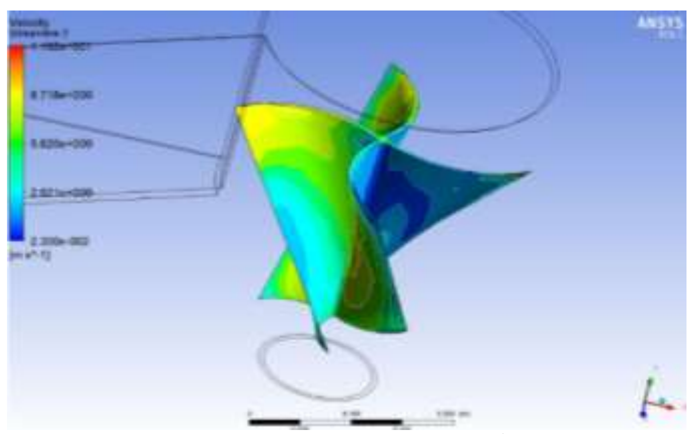

FIGURE 9. Velocity stream lines and the distribution from center to edges

Figure 9 clearly depicts how the wider face of the edges is proving vital in providing kinetic velocity from momentum of fluid to generate electricity. The Figure 10 of velocity contour in the channel shows that the velocity of the water streamlines will increase with the said angle.

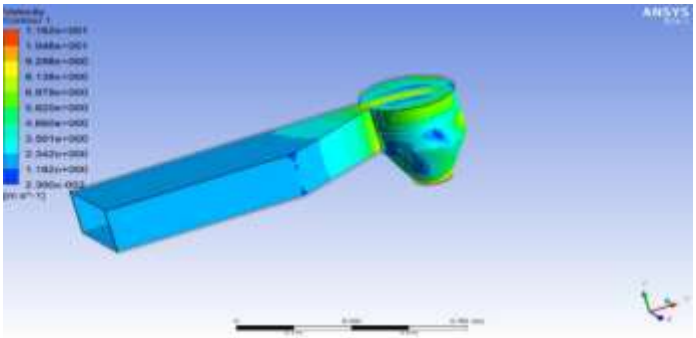

FIGURE 10. Wall velocity contour of inlet channel having notch angle of 153

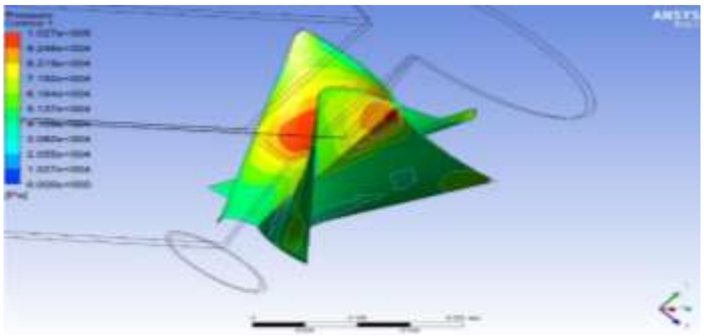

FIGURE 11. Turbine Blade Pressure Contour

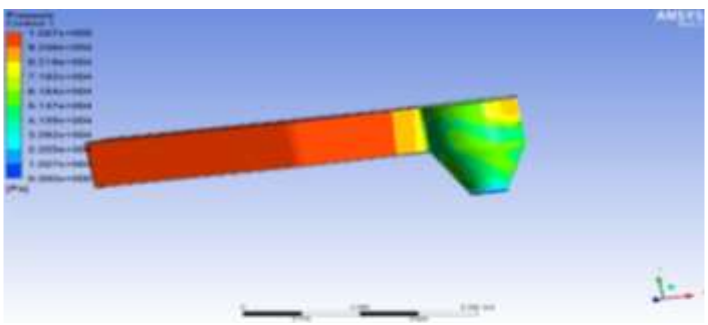

FIGURE 12. Steel Wall channel Pressure Contour

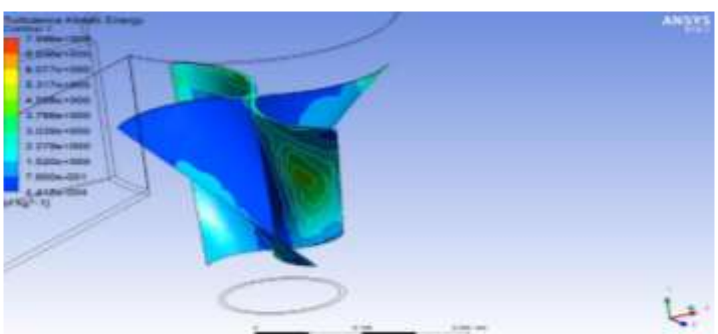

FIGURE 13. Blade Kinetic Energy Impact Contour

From Figure 11, we can see that the steel blade material is bearing a lot of pressure from water and in some time or may be due to pitting corrosion the blade failure will occur. For this, the blades must be optimized through heat treatments and high chromium steel grade must be used. Similarly, if casting must be used instead of welding as fluid impact pressure is very high in the joint region where the blades are attached to the shaft

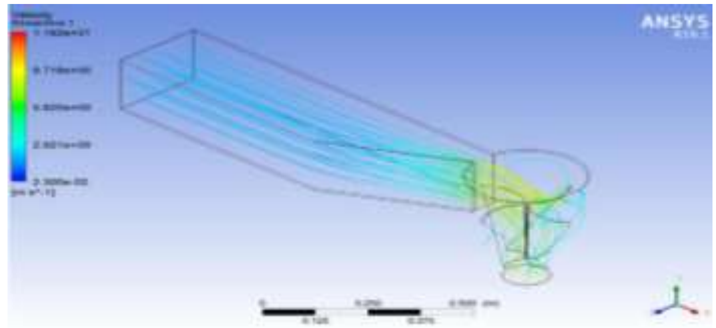

FIGURE 14. Velocity Streamline Flow Behavior Contour

The kinetic energy impact profile in Figure 12 also shows that steel channel is not able to bear the pressure and resulting momentum of the water and it should be replaced by a cement reinforced structure for more durability and efficient output. The Figure 13 of velocity streamline flows show that the whole design is able to produce the vortex in the inlet blade diameter with very high velocity values of 6.7m/s. It also validates that the streamline assumption made.

C. *CIVIL STRUCTURE RESULTS*

The analysis and design shows that the curved part near the exit seems to be the most stressed area Fig. 15.

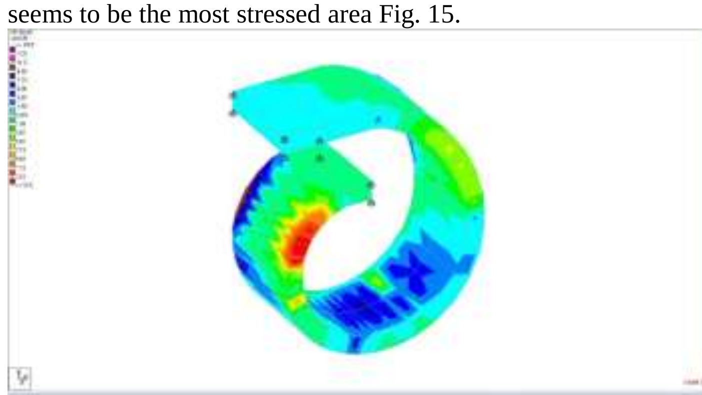

FIGURE 15. Maximum Flexural Stress Diagram

As we move within the water channel, the water gains more and more pressure due to reduced area and hence the stresses are increased accordingly. Against the developed maximum flexural stresses, it is proposed to provide a 150mm thick walls and a transverse reinforcement of 0.270 mm2/mm. In the longitudinal direction, minimum reinforcement will serve the purpose.

IV. CONCLUSIONS

Numerical simulation was made for the design and development of Pico hydro turbine with gravitational vortex for the sites in Punjab where the water flow rate in the canals ranges 0.005-0.01 m^3/sec and available head is 1.5 m. The analysis includes the optimization of basin, blades and rotor for the improved power output of the turbine. The results shows that the tangential velocity on the turbine is increased by using a hybrid blade profile. The numerical simulation confirms that the wider face of the blade edge results in higher kinetic energy.

The results also show that for a notch angle of 153º, there is a substantial increase in water velocity and hence produce higher power output. The blades have to undergo high pressures, therefore a better steel grade with higher yield strength must be used. As pressures are higher near the center so welding should be avoided and casting should be used.

The steel channel can't be utilized for this purpose and reinforced concrete structure must be used. The proposed design for 1.5m head and flooding condition with the flow rate of 0.2 m^3/s, the wall thickness and base thickness should be 150 mm and a transverse reinforcement should be 0.27 mm^2/mm. Localized reinforcements can also be utilized as the curved path is at highest risk.

Water velocities are very high in the inlets and the overall geometry is feasible to provide the kinetic energy to the turbine rotor. The electricity needs for the rural area is limited, so it is concluded that the designed turbine is capable of providing electricity to a small community in the rural area of Punjab. The local production of electricity for small village brings the line losses to very minimum level. The heavy expenses incurred in the distribution of electrical cable from the grid station to remote rural area population can be avoided.

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