# MODELING, SIMULATION AND FABRICATION OF AN UNDERSHOT FLOATING WATERWHEEL

Farid Ullah Khan*, Adeel Ahmed*, Uzair Khan Jadoon*, Fahim Haider*

## ABSTRACT

*This paper presents modeling, simulation and fabrication of an undershot floating waterwheel for power generation for run-of-the-river applications. For the undershot floating waterwheel, analytical modeling and simulation are performed to estimate the optimal design parameters. Moreover, the dependence of output power on various parameters of waterwheel is also investigated during simulations. It is found, during analysis that the water flow velocity is the major factor affecting the output power and due to availability of high flow velocity stream the parameters of the waterwheel, such as, radius and width of wheel can be reduced considerably. For a flow velocity of 1.5 m/s, design estimates for waterwheel producing 1 kW power are obtained with the devised analytical model. The simulations performed for the 1 kW power development, show that a 1 m radius waterwheel with 10 number of blades, each having a width of 1.75 m and height of 0.55 m, are capable of generating the desired power from stream flow velocity of 1.5 m/s. Moreover, a prototype of an undershot floating waterwheel is also fabricated from low weight materials, such as, fiber glass and mild steel square tubes. For electrical power generation a DC generator is coupled with the output shaft of the waterwheel. The developed prototype wheel successfully produced a maximum power of 0.6 kW from a water stream flowing at 1.2 m/s in an irrigation channel.*

**KEYWORDS:** *Floating; Hydel; Modeling; Power generation; Run of the river; Simulation; Waterwheel*

## INTRODUCTION

By the end of 20th century, the whole world felt grave concern about the rapidly depleting energy resources. Moreover, due to the industrial revolution the environmentalists were greatly worried about the extensive emission of carbon dioxide ($CO_2$) that was leading to environmental pollution and global warming. In 2013, it was highlighted by Intergovernmental Panel on Climate Change (IPCC) that the largest contribution in global warming was by carbon dioxide ($CO_2$) that is emitted by fossil fuels combustion[1]. In last few decades immense efforts are being made to reduce fossil fuel emissions and to explore the green technologies for power generation. The renewable energies[2], which are the natural reserves of energy and friendly to environment, need to be efficiently utilized for energy production. The developed countries are trying their best to replace, the thermal power plants (that are using fossil fuels) with the more sustainable power generating units operating on renewable energies. Therefore waterwheels were accredited for their environmental friendliness and being a source of renewable energy[2].

### (a) Renewable energy

The energy that is derived from an inexhaustible energy sources, such as, wind, sun, sea, geothermal or replaceable energy reserves (such as, waste products, crops) is categorized as renewable energy. The three viable areas of renewable energy that are abundantly available and have the immense prospect for power generation are solar, wind and hydel[3]. For the past few decades tremendous amount of efforts are being made to replace the fossil fuel power generation with the environment friendly renewable power plants.

### (b) Wind power

The environmental difference in temperature from place to place cause the air density to vary from region to region and thus originating high speed winds. These high velocity winds can be used to operate wind turbines for the generation of electric power. Throughout the globe there are localities which have tremendous tendency to produce power from the wind. Moreover, the coastal and off-shore areas have greater prospects for wind power generation.

* Institute of Mechatronics Engineering, University of Engineering & Technology, Peshawar, 25120, Pakistan

### (c) Solar power

The solar energy which is abundantly present throughout the planet earth can be used as replacement for fossils fuel. In last few years, several technologies have been developed to convert the solar energy into electrical energy. The most popular among these is the invention of photovoltaic cell. Due to the rapid progress and developments in micro, nano and semiconductor technologies, now more reliable, efficient and low cost photovoltaic cells are being produced for domestic as well as commercial usage. Moreover, the technology for utilizing solar energy for building air conditioning or for solar-thermal power plants is also developing very swiftly.

### (d) Hydro power

In the nature, the hydrological cycle exists, in which the water is evaporated from the oceans into clouds, producing rain onto high grounds which then flows back to the oceans as rivers, streams and tributaries. The flow of this water is normally harnessed to produce power. On natural feasible localities large, medium or small dams have been developed and hydel turbines are being used to produce the electrical power from the stored hydraulic energy. Commonly, where it is not feasible to install large size hydel generating units, medium or small dams are constructed to produce moderate powers. Micro or small scale hydropower[4,5] is classified in Table 1.

In Pakistan, the recoverable hydropower potential is estimated to be approximately 40,000 MW. However, due to economical, social and political constraints, Pakistan has been utilizing only about 16 % of the total hydropower potential[6]. Although there are natural locations where mega or large dams can be developed but unfortunately these projects are lingering for the last few years. In Pakistan, over 70 % of the population lives in rural areas. Due to the current economical situation, it is not feasible to connect the far-flung remote rural areas to the National grid. In such situations, the standalone power systems that are using small, pico or micro hydro turbines are an economical, viable and attractive solution. For small localities, where hydro energy is available in the form of river or stream, micro or pico-hydel turbines can be installed for production. However, the design and fabrication of hydel turbines needs specialized knowledge, skills and fabrication facilities, which normally leads to the high cost of the overall project. Moreover, due to the simple design and fabrication, attention could also be focused on run-of-water generating units, such as waterwheels. The main advantage of waterwheel over the turbine is that these do not require dams, (as in case of turbines) but rather can generate power from the running water in rivers or streams. Recently, in the technologically advanced and developing countries, the waterwheel usage has re-emerged. The production through waterwheel units is actually a re-emerged renewable low cost technology for micro and pico power generation. Within this paper the intention is to provide domestic power in Pakistan by producing the power with a pico-hydropower floating waterwheel.

**Table 1. Classification of low power hydro systems**

| Hydropower | Range (kW) |
|---|---|
| Pico hydropower | **Up to 5** |
| Micro hydropower | 5–100 |
| Mini hydropower | 101–1000 |
| Small hydropower | 1001–15000 |

## WATERWHEEL

Waterwheels are among the oldest hydel equipment known to human beings and have been in use for the last few centuries[7]. Previously, waterwheels were commonly fabricated from wood. In the very past, the difference between kinetic energy and potential energy of water was not more clear, and hence, the efficiencies of the developed waterwheels were on the lower side. However, due to the advancements in hydraulic engineering and the progress in the materials sciences, development of sophisticated computerized numerical control (CNC) production machines and the accessibility of the CAD and CAM tools, the design, shape, size, output power generation and efficiency of the currently developed waterwheels have significantly improved. In the countries like, Germany and Switzerland, even after the invention and development of hydraulic turbines and steam engines, work on waterwheels were performed and these were further developed[8]. The waterwheel design, development and performance reached to optimum levels at the start of the twentieth century. The design of waterwheels has become compact. Up till 1950's, the utilization of waterwheels was wide spread throughout the world, however, afterward, due to the emergence of novel power generation technologies the focus has shifted to other energy sources[8]. Currently, in waterwheel technology, very little is known about the level of advancements obtained in the past and moreover, the well developed and organized research work is not easily accessible.

**(a) Development of modern waterwheel**

Even now, waterwheels are assumed to be an empirical development originated in the pre-steam technology time. In 1759, conducting tests on a number of waterwheel models, John Smeaton was the first engineer who determined the efficiency of waterwheels[9]. During model testing it was found that efficiency of over shot wheels was more than 60 %, however, for undershot wheels the efficiency reached up to a maximum 30 %. The advancement in hydraulic engineering and the invention of new materials, such as, wrought iron, which had much higher strength than wood and permitted more hydraulically designed shapes, more efficient waterwheels were developed that converted hydel energy from very low heads. In the nineteenth century and during the industrial revolution and even in the beginning of early twentieth century, waterwheels significantly remained the most important hydel energy conversion machines[10]. Even after the inventions of the water turbines (after 1850), waterwheels existed in operation as the main power production machines in huge numbers throughout Europe. In the 1850's, approximately 25,000 to 30,000 waterwheels were in service in England only. However, a round 1925 there were 33,500 waterwheels in operation in Germany[7]. In the same time in one of the German provinces, Baden-Württemberg (35,000 km² area), around 3,554 waterwheels were extracting the hydraulic energy. However, in 1977, this number of waterwheels had drastically lowered to only 18. In comparison to steam engines, the relatively low cost and comparatively high efficiency for a broad range of water discharge were the main reasons of using waterwheels over steam engines[11]. In the late nineteenth century and during early twentieth century, the design and production techniques of waterwheel were part of civil and mechanical engineering courses[9] in universities and several books related to the waterwheel's design were available in print up till 1939. However, due to the development of high efficiency steam turbines, hydraulic turbines and internal combustion engines, up till 1950's to 1960's nearly all waterwheels vanished and along with them the technical literature related to their design and performance.

**(b) Types of waterwheel**

The three main types of waterwheel are overshot, breast shot and undershot waterwheel[8].

**(i) Overshot waterwheel**

The schematic of overshot waterwheel is shown in Figure 1. Water enters the overshot waterwheel from the top. In comparison to undershot wheels, overshot wheels obtain a double advantage from gravity. During the operation, in overshot wheel not only the flowing water momentum is fractionally transferred to the wheel's blades but also the weight of flowing water over the blades induces extra energy. The average efficiency[12] of overshot waterwheel is about 63%. However, overshot waterwheels require precise designing and significant pressure head, which normally attributes to extra cost for constructing of a dam, millpond and waterways.

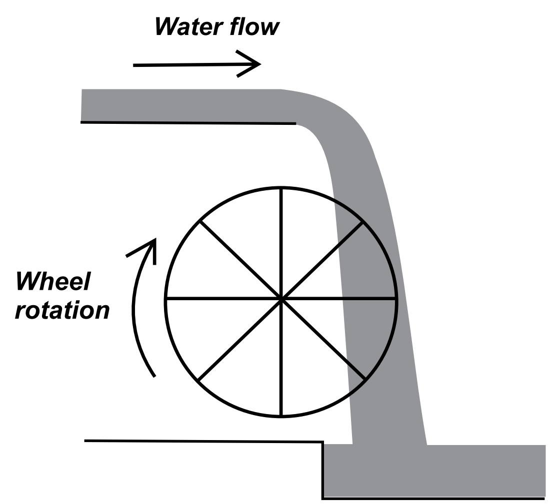

Figure 1. Schematic of overshot waterwheel.

**(ii) Breast shot waterwheel**

The breast shot waterwheel is shown in Figure 2. The level of the water in breast shot waterwheel normally lies near to the axis of the wheel. This type of wheel normally requires a head of 1.5 m to 4 m for their

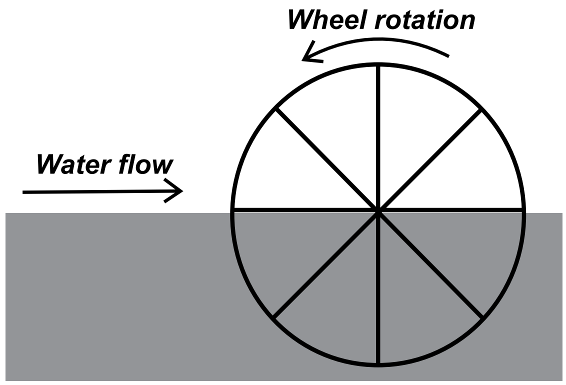


Figure 2. Schematic diagram of a Breast shot waterwheel

operation[8]. The efficiency of breast shot waterwheels is lower than the overshot wheels, however it is more than that of undershot waterwheels.

**(iii) Undershot waterwheel**

The undershot waterwheel which is also known as stream wheel is shown in Figure 3. In undershot wheel, entering water level is always below the wheel axis[12]. Unlike overshot wheels, undershot wheels obtain no advantage from the water head and due to this reason these wheels are more suitable for shallow water streams and rivers. The undershot wheels are simpler in design and fabrication, and are much cheaper than the other types of waterwheels. Moreover, these wheels contribute much less impact on the environment, since these wheels do not require much change to the flowing stream or river.

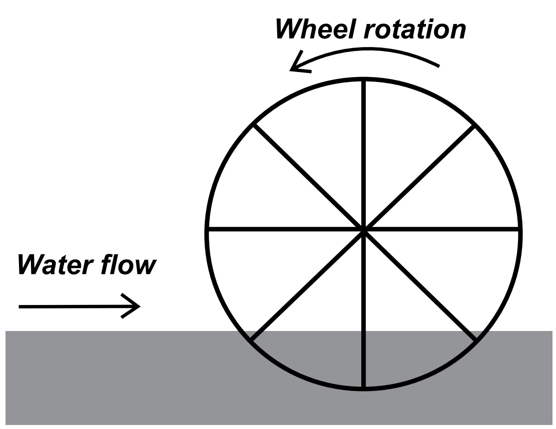


Figure 3. Undershot waterwheel.

## FLOATING WATERWHEEL

In recent times, the concept and development of floating waterwheels have originated and gained importance due to the increase in power demands and awareness of climate change and global warming. Likewise stationery waterwheels, floating waterwheels do not require civil structure like dam, waterways or channel. Moreover, these are moveable machines and can be operated at any site, where relatively high velocity water is flowing. A floating waterwheel commonly consists of floats, frame, wheel (rotor), gear box or belt and pulleys system, and electrical generator, as shown in Figure 4.

A floating waterwheel was developed in England[13] by the researchers of University of Southampton. The design was based on Blade Element Momentum Theory that uses similar ideas as those used for vertical axis turbines. The waterwheel had a diameter of 2 m and blade width of 1 m constructed using exterior grade plywood. Softwood stiffeners were used to minimize blade deflection at the outer edge. Waterwheel along with pulleys and generator rested upon a pair of 4.5 m long floats or hulls. The completed floating waterwheel was towed behind a motorboat where it produced a power of 45 W at an average flow velocity of 1.19 m/s. It was found that concept is sound although greater investment was required with regards to the materials and both aerodynamic and hydrodynamic design of waterwheel to ensure economically viable system.

Zoe Jones in 2005 developed a mathematical model[8] for undershot floating waterwheel using drag force equation for bodies moving in fluid. A basic MathCAD model was created describing movement of blade from vertical portion to position where it leaves the water. By altering the waterwheel parameters individually by 50 % and noting the corresponding output power increase the flow velocity was rendered as most influential variable as with a 50% increase it produced a 350 % increase in power output followed by number of blades and radius of waterwheel. Surprisingly increase in draft value produced no increase in output power. Zoe Jones concluded that waterwheel is a viable aesthetically pleasing option for domestic energy generation but greater investigation is needed in gearbox and generator selection to overcome slow rotational speed problem in waterwheels.

This work reports the design, analytical modeling simulation and fabrication of an undershot waterwheel developed for pico power generation.

**Floating waterwheel prototype**

The solid model of the floating waterwheel opted in this work is shown in Figure 4. An undershot type wheel is chosen for the floating waterwheel as it is most suitable for low head flow that are normally available near shore tidal induced currents or in low land rivers or streams. As the proposed floating waterwheel is an impulse device, working through extraction of kinetic energy from the flowing water.

The development of conventional waterwheels is hampered by requirement of narrow streams with smooth bed and sides as the construction of channel and installation site adds significantly to the overall cost of waterwheel. Furthermore, high accuracy of construction and installation make them unsuitable for developing countries like Pakistan. The construction cost for an undershot waterwheel can be significantly reduced using floats for wheel to rest upon instead of building a separate channel. Based on the fact that low velocity and negligible head flow sites are readily available in Pakistan in form of a vast and comprehensive network of irrigation canals, idea of floating undershot stream wheel can be easily employed to generate electric power for remote localities.

Although there is significant variation in volume of flow from year to year, the Indus River System has high degree of regulation, generally attributable to a large component of snow and glacier melt. The Indus Basin Irrigation System comprises of three major reservoirs, 16 barrages, 2 head-works, 2 siphons across major rivers, 12 inter river link canals, 44 canal systems (23 in Punjab, 14 in Sindh, 5 in Khyber Pakhtunkhwa and 2 in Balochistan) and more than 107,000 water courses. The aggregate length of the canals is about 56,073 km[14]. In addition, the watercourses, farm channels and field ditches cover another 1.6 million km. Most of these canals are well constructed having smooth bed and cemented sides. Floating waterwheels can be installed easily on these canals and power can be extracted without disturbing water flow.

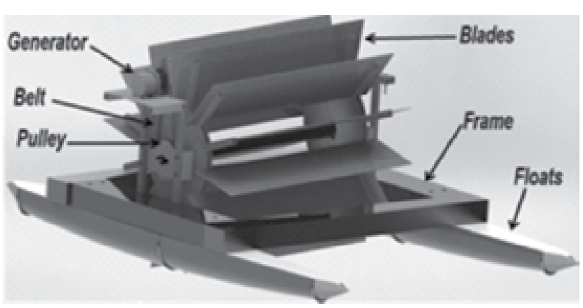


Figure 4. Solid model of floating undershot waterwheel.

## ANALYTICAL MODELING OF FLOATING WATERWHEEL

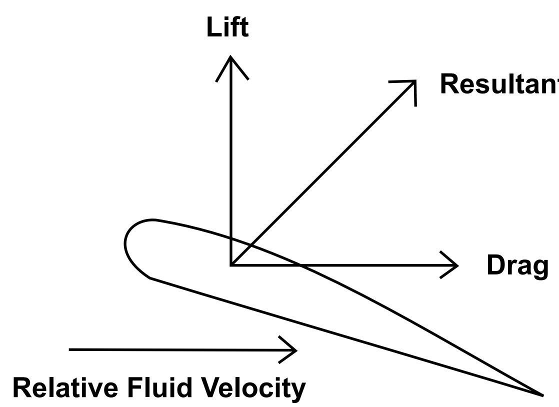


Figure 5. Flow over an airfoil.

When flow occurs around an immersed body, the immersed body experiences a force known as drag force[11]. The drag force can be resolved into two rectangular components, Lift and Drag as shown in figure 5.

The drag force[11]

$$F = 0.5 \times p \times C_a \times A \times V^2 \quad (1)$$

in the direction of motion depends upon the characteristic area ***A*** of the immersed object, density ρ of fluid, flow velocity ***V*** and coefficient of drag $C_d$. Drag remains the same whether the body moves through the fluid or the fluid flows around the body as long as the relative motion remains the same.

Drag force acts on blades of waterwheel as they move through water. For the waterwheel shown in Figure 6,

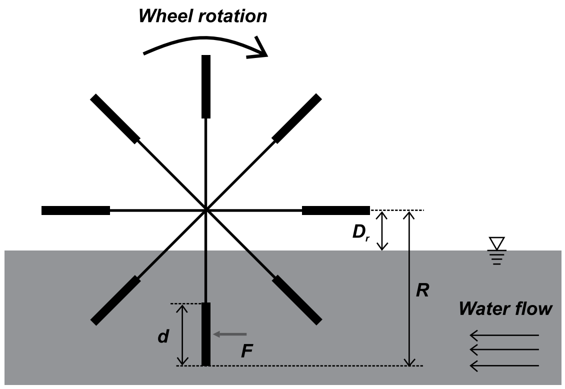


Figure 6. Side view of undershot waterwheel.

the drag force[8]

$$F = 0.5 \; x \; p \; x \; C_a \; x \; w \; x \; d \; x \; V_r^2 \qquad (2)$$

of Equation (1) can be modified and expressed in terms of width *w* of the blade, immersed height *d* of

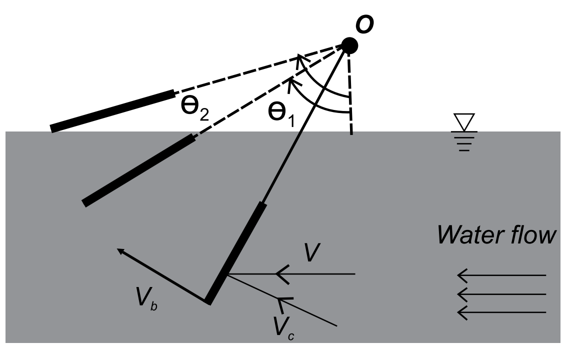


Figure 7. Side view of single blade of waterwheel during rotation.

the blade and relative velocity $V_r$ between the blade and water (Equation 2).

The relative velocity

$$V_r = V_c - V_b \qquad (3)$$

is difference between blade velocity $V_b$ and the component of flow velocity $V_c$ in the direction of blade motion. In order to absorb power blade must rotate at a velocity smaller than flow velocity given by where *p* is a constant having a value between 0 and 1. For maximum power absorption, Denny[12] calculated the optimum value of p as 0.33.

In Figure 7, the velocity component

$$V_c = V \; x \; cos\theta$$

in the direction of blade motion depends on the blade's rotation angle and the flow velocity *V* of the water.

By substituting for $V_c$ and $V_b$ in Equation (3), yields the relative velocity

$$V_r = V \; x \; (cos \; \theta - 0.33) \qquad (4)$$

in terms of blade's rotation angle θ.

The drag force acting on blades of waterwheel varies with the angle of rotation of the blade. The drag force is maximum when blade is in vertical position that is perpendicular to the flow direction and is minimum when blade is just leaving the water level.

During wheel rotation for angle, height of the blade immersed in water remains constant as blade is fully submerged. $\theta_1$ is the angle of rotation at which blade starts leaving water level. By substituting coefficient of drag[8], $C_d$ = 1.5, water density ρ = 1000 kg/m$^3$ and the relative velocity $V_r$, Equation (4), in Equation (2), yields the drag force

$$F(\theta) = 750 \; x \; w \; x \; d \; x \; V^2 \; (cos\theta - 0.33)^2 \qquad (5)$$

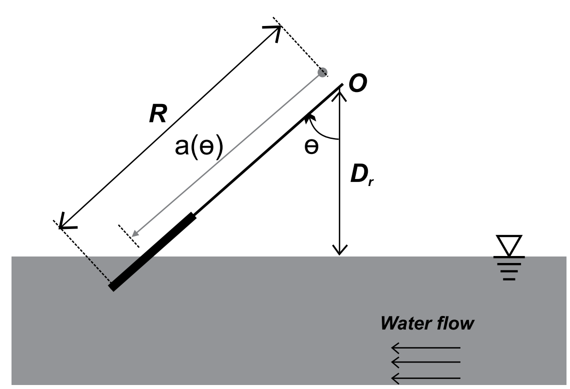


Figure 8. Rotation of the wheel as the blade starts leaving the water level

that acts on blades of waterwheel for the wheel rotation .

After rotation $\theta_1$, blade starts leaving the water and immersed height $d$ of blade is no longer constant. The decrease in immersed height causes a decrease in submerged blade area , as shown in Figure 8.

By accounting for this change in immersed area of the blade, the drag force

$$F(\theta) = 750 \times w \times (R - a(\theta)) \times V^2 (\cos\theta - 0.33)^2 \quad (6)$$

that acts on the blade for angle of rotation for the remaining journey of the blade is obtained. In figure 8, the variable length which is expressed in terms of draft $D_T$ can be substituted in equation (6) to obtained the drag force

$$F(\theta) = 750 \; x \; w \; x \left(R - \frac{D_T}{\cos\theta}\right) x \; V^2 (\cos\theta - 0.33)^2 \quad (7)$$

as a function of draft $D_T$ and radius $R$ of the waterwheel.

The Drag Force $F$ acting on the blade of waterwheel along the moment arm causes to produce moment

$$M(\theta) = 750 \; x \; L \; x \; w \; x \; d \; x \; V^2 (\cos\theta - 0.33)^2 \quad (8)$$

about the center $O$ of waterwheel for angle of rotation. Similarly for angle of rotation, the moment

$$M(\theta) = 375 \; x \; w \; x \left(R^2 - \left(\frac{D_T}{\cos\theta}\right)^2\right) x \; V^2 (\cos\theta - 0.33)^2 \quad (9)$$

is produced about wheel center $O$.

The work done on the blade of the waterwheel can be obtained by taking integral of moment produced at wheel center during blade journey through water. During rotation of blade from to , the work

$$W = \int_0^{\theta_2} M(\theta) \, d(\theta) \quad (10)$$

done on the blade of waterwheel can be utilized to obtained a relation for the total work done

$$W_T = 2 \; x \; N \; x \left(\int_0^{\theta_1} M(\theta) \, d(\theta) + \int_0^{\theta_2} M(\theta) \, d(\theta)\right) \quad (11)$$

for the complete revolution of the wheel in terms number of blades N of the wheel.

The output power

$$P = W_T / t \quad (12)$$

of waterwheel can be obtained from the total work done $W_T$ on blades in one revolution and the time

$$t = \frac{2 \; x \; \pi \; x \; R}{p \; x \; V} \quad (13)$$

required for the wheel to complete one rotation.

Equation (11), (12) and (13) yield the power output

$$P = \frac{247.5 \times w \times V^3 \times N}{2\pi R} \times \left[\begin{array}{l} 2 \times L \times h \times \left(\frac{1}{2}\theta_1 + \frac{1}{4}\sin(2\theta_1) + 0.109\theta_1 - 0.33\sin\theta_1\right) \\ + \left(\begin{array}{l} \frac{R^2}{2}(\theta_2 - \theta_1) + \frac{R^2}{4}(\sin 2\theta_2 - \sin 2\theta_1) + 0.109R^2(\theta_2 - \theta_1) - 0.66R^2(\sin\theta_2 - \sin\theta_1) \\ -(D_T)^2(\theta_2 - \theta_1) - 0.109(D_T)^2(\tan\theta_2 - \tan\theta_1) \\ -0.66(D_T)^2\left[\ln(\sec\theta_2 + \tan\theta_2) - \ln(\sec\theta_1 + \tan\theta_1)\right] \end{array}\right) \end{array}\right] \quad (14)$$

of the waterwheel for one complete revolution

**Table 2. Flow conditions and different parameters of floating waterwheel used for simulations**

| Parameter | Dimension/value |
|---|---|
| Water flow velocity | **1.5 m/s, 1.7 m/s, 2 m/s** |
| Draft | 0.3 m |
| Wheel diameter | 0.75 m – 3 m |
| Blade height | 0.5 m, 0.8 m |
| Blade width | 1 m, 1.2 m, 1.5 m |
| Blade Rotation angle (Leaving angle) | 70.7° |
| Number of blades | 10 |
| Power factor | 0.33 |

## SIMULATION AND DISCUSSION

The analytical model developed for the undershot floating waterwheel is simulated to analyze the dependence of generated power on various waterwheels' parameters and flow conditions. MATLAB software provides an interactive environment for numerical computation to analyze the data, develop algorithms, models and applications. Following plots have been obtained using MATLAB that help to study the behavior of output power and design model for any targeted output value. The flow conditions and the waterwheel parameters used during the simulation are listed in Table 2.

In the simulations, a draft of 0.3 m is used for the

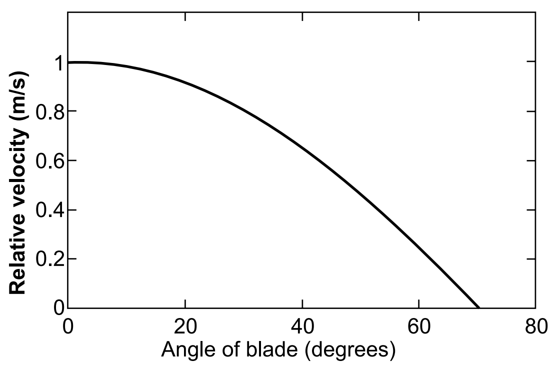


Figure 9. Relative velocity as function of angle of blade

floating waterwheel and the design parameters of the waterwheel are pridicted for the three different flow conditions of 1.5, 1.7 and 2 m/s.

Figure 9 shows the relative velocity of the wheel as a function of angle of rotation of blade. The simulation is performed for the water flow velocity V = 1.5 m/s and is the result of Equation (4). Relative velocity between blade and water decreases as the rotation angle of the blade increases and it become zero when the blade rotation angle is , which suggests that at blade's rotation angle there is no difference between blade velocity and component of flow velocity in direction of blade motion. Figure 9: Relative velocity as function of angle of blade

Owing to its dependence on relative velocity the drag force on wheel blades also shows similar behaviour as shown in Figure 10

For several water flow velocities, the drag force as a function of the rotation of the wheel's blade is shown in Figure 10. Equation 5 is used for the computation and for the simulation the blade width w = 1.5 m and blade height d = 0.5 m are used. Drag force decreases with the blade's angle of rotation from to and this is attributed to the decrease in relative velocity. It can also be viewed as decrease in area of blade perpendicular to

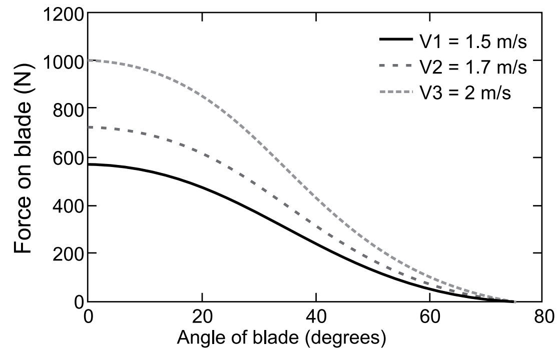


Figure 10. Force on blade during rotation of wheel's blade at different flow velocities.

the flow velocity. At , the force is maximum because the water is striking the blade at right angle (as shown in Figure 2), however, at the force becomes zero due to the fact that relative velocity is zero. At this angle water no more exerts any force on the blade and rather blade has to exert force on water as it moves through water afterwards. From Figure 10 it is evident that force will become zero at every time regardless of the flow velocity. The drag force increases as the flow velocity of the flowing water is increased, however, the force become zero at every time regardless of the flow velocity. For a water flow velocity of 1.5 m/s the maximum force of 580 N is obtained and for 2 m/s the maximum

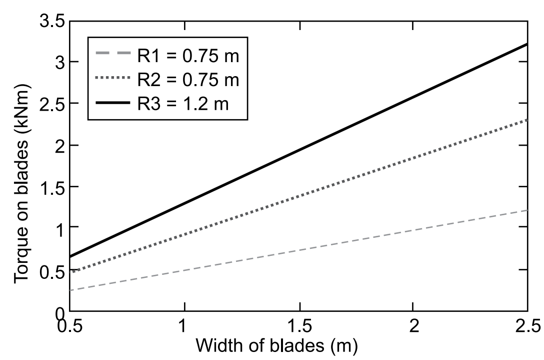


Figure 11. Torque as a function of blade's width at various radii of the waterwheel.

force of 1000 N is to be generated which is about an increase of 95%.

The dependency of the generated torque by the wheel on the width of the blade and the radius of the wheel is shown in Figure 11. For the computation, Equations (8) and (9) are utilized to obtain the plots. Increasing blade's width increases the blade's area and more force is exerted that in turn generates high torque. Waterwheel having blades of width of 0.5 m and radius of 0.75 m produces a torque of 0.5 kNm at its shaft. However, when the width of blades is doubled, the same wheel generates a torque of 1 kNm, showing 100% increase

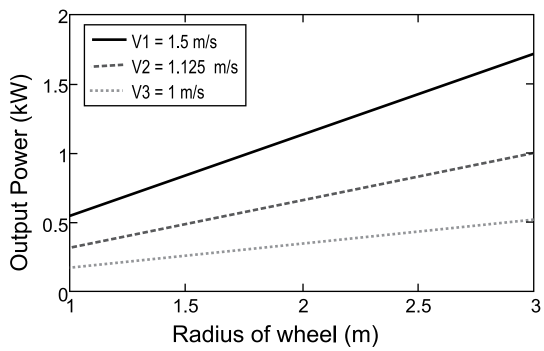


Figure 12. Variation of output power with flow velocity.

in torque. The simulation indicates that rendering width of blades as an important factor affecting the torque or output power of the wheel.

Figure 12 shows the output power as a function of flow velocity keeping radius, width and number of blades of waterwheel constant. Large increase in output power is observed by increasing flow velocity which describes flow velocity as the most influential parameter for contribution to the output power. This behavior of output power is well justified by Equation (1) where

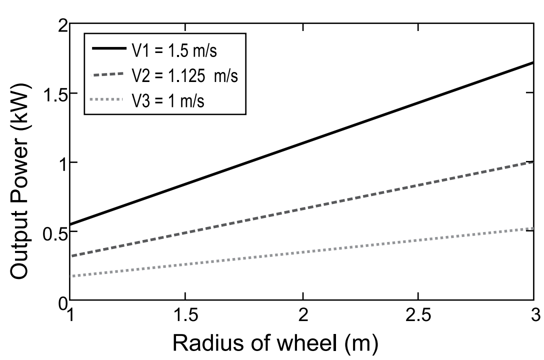


Figure 13. Variation of output power with radius of wheel.

flow velocity variable holds square power. Greater flow velocity results in more force exerted on blades and hence more power is produced. At 1 ms$^{-1}$ the output power is 0.25 kW for N = 10 and at 1.5 ms$^{-1}$ the output power is 0.7 kW. This shows that 50% increase in current velocity results in 350% increase in output power.

Figure 13 shows the effect of increase in radius of

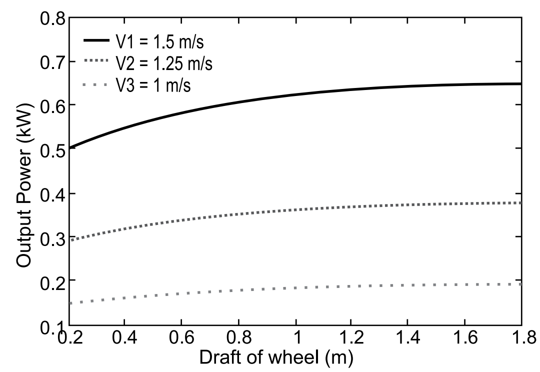


Figure 14. Variation in output power with draft of wheel

waterwheel on the output power for different values of flow velocity. Increase in radius of waterwheel also increases the output power. However, this increase is not as significant as in case of increase of blade's width or increase of flow velocity. Increase in radius results in larger torque, however, it also results in more time for wheel to complete one rotation (angular speed) and eventually due to the output power does not show significant increase. For a flow velocity of 1.5 m/s, a waterwheel having radius of 1 m produces a power of 0.5 kW. However, a power of 1.5 kW is produced when the wheel radius is increased to 3 m.

The effect of increased time required to complete one rotation due to increase in radius on output power is more evident in Figure 14 where radius is increased by increasing draft which is the vertical distance between wheel center and water level.

By increasing the draft value, radius of water is increased outside water and immersed height of blade in water is not increased. Increased radius results in more time to complete one rotation. Moreover, the proportion of time during which blade moves through water is small as compared to total time taken to complete one rotation.

Hence very small power is absorbed. That is why after small initial increase the graph of power becomes almost

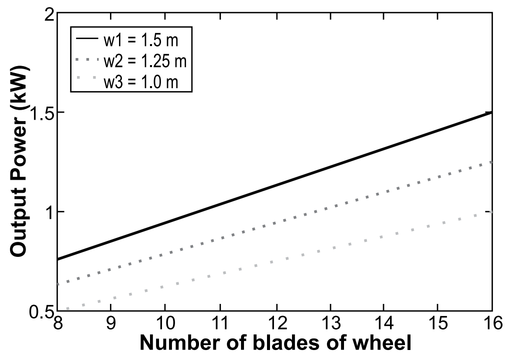


Figure 15. Variation in Power with increasing number of blades.

constant regardless of large increase in radius.

The output power dependency on the number of blades at different blade's widths is shown in Figure 15. Increasing the number of blades increases the output power as more blades will absorb more power. There is no information available about optimum number of blades for a waterwheel having a certain radius. The reason for the waterwheel with more blades producing more power than the wheels with fewer blades is that when it had fewer blades the water strikes each blade and between each strike is a delay. This delay allows the wheel to slow down so less power is produced. But when there were more blades there is less time between each strike so less speed was lost. Since less speed was lost the waterwheel could produce more power. However, practically too many blades will affect each other's force fields and cause water not to flow freely through blades and results in reduction in power.

## SIMULATION OF 1 kW OUTPUT POWER

Utilizing analytical models and simulation results obtained earlier, a floating waterwheel is designed that can generate 1 kW power. For this purpose some parameters are kept constant and others are varied to decide about the dimensions of the desired floating waterwheel.

The current velocity of 1.5 m/s recorded at the canal located at Phase 7, Hayatabad, Peshawar is used for designing and simulation of 1 kW floating waterwheel. Output power increases with increased radius of the wheel. Radius of 1 m is selected to keep size and cost of waterwheel in range so that it is easy to handle and financially affordable.

No design information is available regarding the number of blades for a fixed radius. For a waterwheel of radius R = 1 m, Ten blades will have an angle of $36^{O}$ in between each other and leaving enough space for water to flow through blades easily and efficiently.

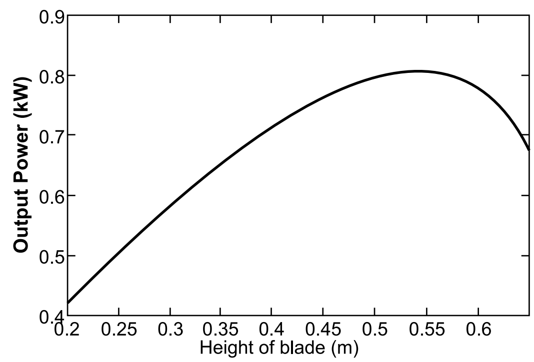


Figure 16. Variation in power with height of blade.

To decide about leaving angle, Figure 10 needs to be revisited. The drag force becomes zero at about and

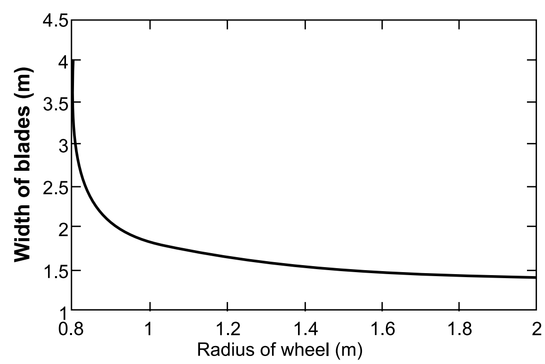


Figure 17. Variation of required width with radius for 1 kW power.

tends to be negative after . This shows that after no power is absorbed, rather the blade has to exert force on water to move further thus producing negative power. It is therefore advisable to keep leaving angle below. In reality, the value of leaving angle is practically controlled by draft. Draft of the floating waterwheel is selected such that the blade of waterwheel is out of water when.

Using Figure 8, draft

$$D_T = R \ x \ cos \ \theta_2 \tag{15}$$

**Table 3. Design estimates of floating waterwheel for 1 kW power production**

| Parameters | Dimensions |
|---|---|
| Radius of wheel | **1 m** |
| Depth of blades | 0.55 m |
| Width of blades | 1.75 m |
| Draft | 0.3 m |
| Leaving angle | $70^O$ |
| Number of blades | 10 |
| Number of blades | 10 |

comes out to be 0.33 m for a radius of R = 1 m and blade leaving angle of $70.7^O$.

After selecting the radius and draft for floating waterwheel, the immersed height and width of blades need to be obtained for maximum power output. Figure 16 shows power output as a function of height of the blades for a radius R = 1 m and draft of $D_T$ = 0.33 m.

From Figure 16 the height of blade for maximum power output can be easily determined as 0.55 m.

Figure 17 gives the value of required width of a blade for given radius of a waterwheel having blade height of 0.55 m, draft of 0.33 m, leaving angle of , installed in a flow velocity of 1.5 m/s and producing 1 kW power. Small radii waterwheels require more width and vice versa. Figure 17 shows that for large radii despite large increase in radius of waterwheel the required width do not show significant decrease. It can easily be determined that the width of blade for a 1m radius waterwheel to produce 1 kW output power is 1.75 m. (Table 3)

## FABRICATION OF 1 kW FLOATING WATERWHEEL

The main parts of the floating waterwheel prototype, such as shaft, blades frame, floats frame, pulleys boxes for electric generator and pump are fabricated from mild steel (MS), however, for floats and blades fiber glass is used (Table 4). The initial prototyping of the floating waterwheel is shown in Figure 18. The shaft, Figure 18(a) is designed and produced from MS rod. Aluminum alloy discs are used to produce the hub for rotor, Figure 18 (b). Fiber glass sheet is attached to the blade frame (Figure 17 (c)) made from light weight MS square tube, Figure 17 (d). Two self-aligned roller bearings, Figure 18(e) are selected to support the assembled rotor, Figure 18 (f) on the main frame. The MS square tube box, Figure 18 (h) is fabricated to support the two pulleys used for the power transmission from the rotor shaft to

**Table 4. Parameters and dimensions of the developed floating waterwheel**

| Main part | Parameters | Value |
|---|---|---|
| Rotor | Radius of wheel | 1 m |
| | Depth of blades | 0.55 m |
| | Width of blades | 1.75 m |
| | Number of blades | 10 |
| Floats | Length | 3 m |
| | Width | 0.36 m |
| | Height | 0.36 m |
| Generator pulleys | Big pulley diameter | 0.6 m |
| | Small pulley diameter | 0.05 m |
| | Speed ratio | 12 |
| Pump pulleys | Big pulley diameter | 0.5 m |
| | Small pulley diameter | 0.05 m |
| | Speed ratio | 10 |
| Electric generator | Operating voltage | 12 V |
| | Maximum current | 0.8 A |
| Pump | Maximum suction head | 8 m |
| | Maximum delivery head | 40 m |
| | Maximum discharge | 0.5 lit/s |
| | Power consumption | 0.37 kW |
| Battery | Operating voltage | 12 V |
| | Maximum current | 0.6 A |
| Waterwheel Overall size | Length | 3 m |
| | Width | 2.06 m |
| | Height | 2.08 m |

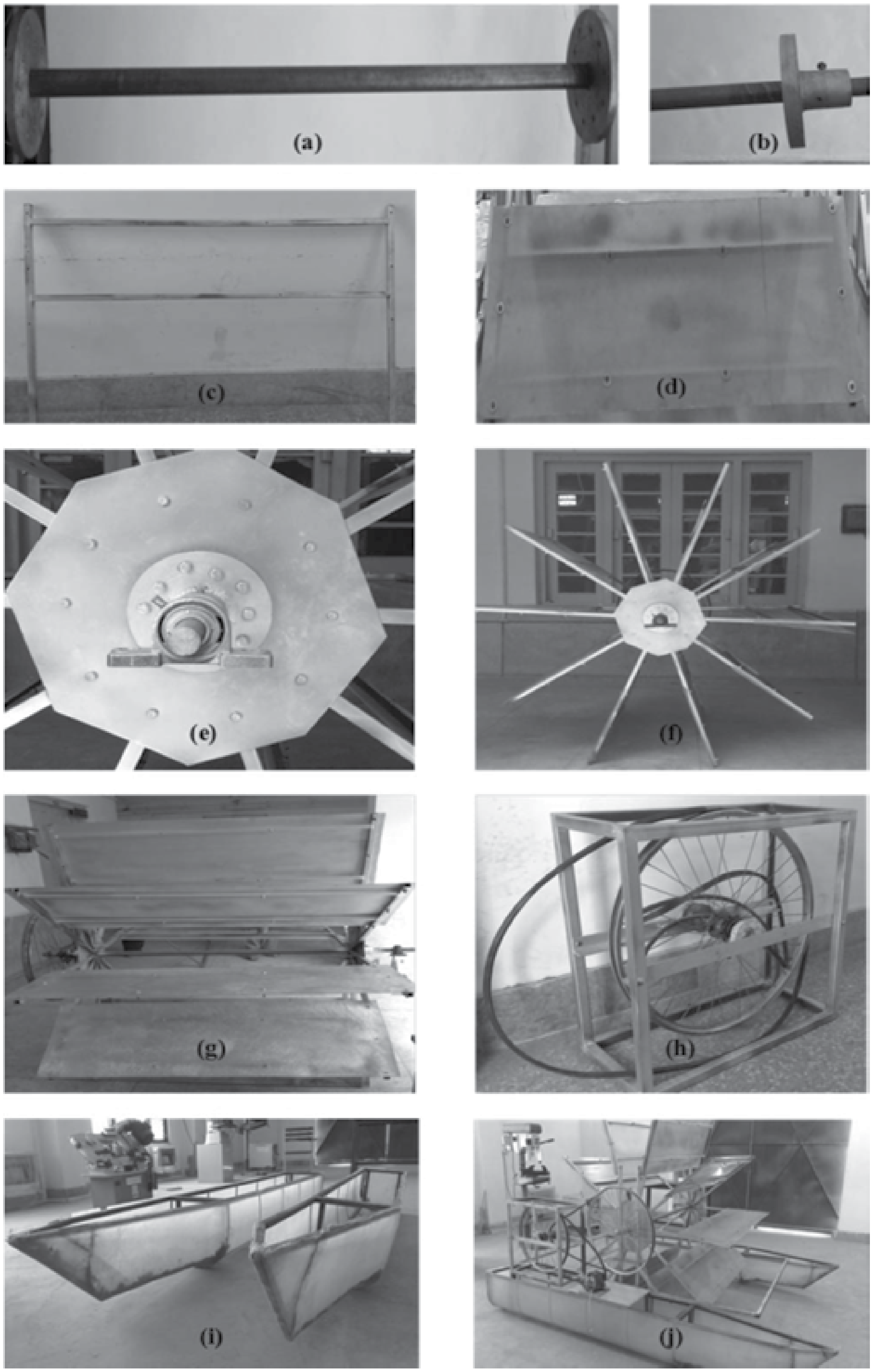


Figure 18. Fabrication of initial prototype floating waterwheel: (a) Shaft, (b) rotor collar, (c) blade frame, (d) blade made from fiber glass, (e) self-aligned roller bear on shaft, (f) fabricated rotor side view, (g) Fabricated rotor front view, (h) pulley box, (i) unfinished floats and (j) initial assembled prototype floating waterwheel.

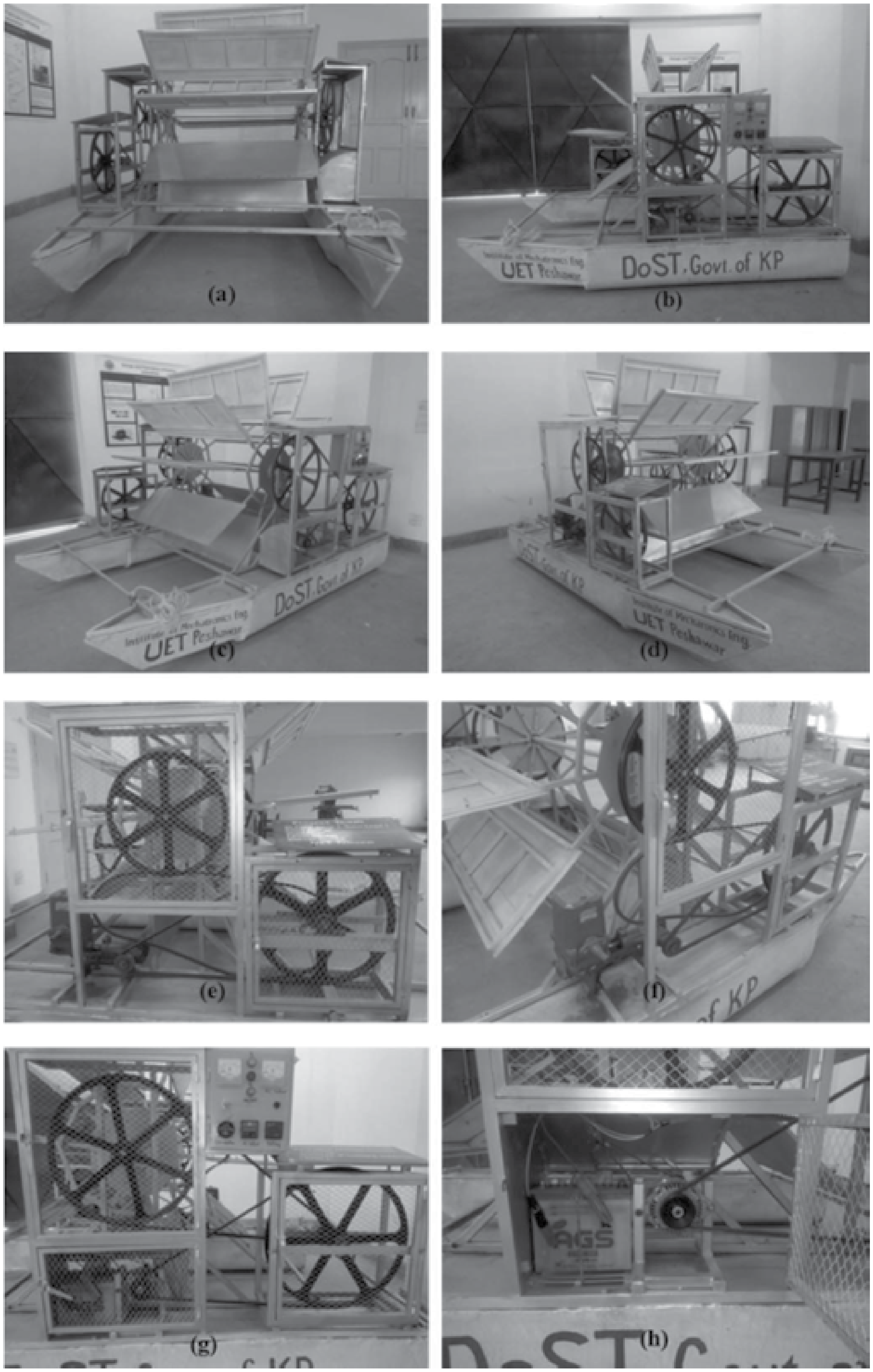


Figure 19. Fabrication of optimized prototype floating waterwheel: (a) Floating waterwheel front view, (b) side view, (c) right isomeric view, (d) left isomeric view, (e) pulleys and pump assembly, (f) pump close up, (g) pulleys and generator assembly and (h) battery and generator close up.

the driven machines (electric generator and pump). On the floats frame (made from MS square tube), fiber glass cover is fabricated to produce the floats, (Figure 18 (i), for the waterwheel. Initial assembly of the prototype floating waterwheel is shown in Figure 18 (j). After development of initial prototype floating waterwheel, it is tested preliminary for power generation, rotor speed, buoyancy and vibrations. When satisfactory results were obtained from the initial prototype floating waterwheel, afterward a better designed and optimized waterwheel is developed which is shown in Figure 19. In the optimized waterwheel a hydraulic pump (Figure 19 (f)) is also mounted on top of the second float in order to counter balance the electrical generator and battery located on the other float. Moreover, the pump could be utilized to supply the water from the river or canal bed to the high elevation areas for irrigation purposes. Two ropes are also attached to either float to control and adjust the orientation of the waterwheel against the flowing water.

The optimized floating waterwheel is tested in open channels, where the flow velocity ranges from 1 to 1.2 m/s. The operation of the floating waterwheel was quiet satisfactory. Electrical bulbs and heating element were used as a load on the generator during operation. At a flow speed of 1.2 m/s, it produced a maximum power of 0.6 kW. The losses in the system are attributed to electrical generator efficiency (less than 100%), fabrication uncertainty, misalignment, specifically on the pump side of the waterwheel. However, due to precise alignment and for the flow condition of about 1.5 m/s, the power production from the waterwheel could easily be increase up to 0.8 to 0.9 kW. Moreover, by a little bit of over sizing on the rotor part, power generation could also be increased up to 1 kW, even at low flow speeds of water in the channel.

## CONCLUSIONS

Analytical modeling, simulation and fabrication for an undershot floating waterwheel is reported in this work. Floating waterwheels have the preference over other hydropower generation machine due to the capability of the power generation from run-of-river conditions. These waterwheels not require any water dam or channel for the operations and can be operated in any location where water is flowing relatively at high velocities. Simulations are performed for different flow conditions to predict the optimized design parameters for an undershot waterwheel. Utilizing the simulation result a prototype undershot floating waterwheel is also fabricated and briefly tested. The model's simulations and the experimental results obtained from the developed prototype waterwheel suggested that the floating waterwheels are beneficial and could be further developed for power production in the Pico range (up to 5kW).

## ACKNOWLEDGEMENT

The authors acknowledge the funding provided by the Director of Science & Technology (DoST), Government of KP, Pakistan for the development of the floating waterwheel.

## REFERENCES


1. *Stocker, T. F., Dahe, Q. and Plattner G-K., 2013. "Technical Summary in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 2013". Available from: http://www.climatechange2013.org/images/report/WG1AR5_TS_FINAL.pdf [Cited 20 Oct 2014].*

2. *Ferry R. and Monoian E., 2012. "A field guide to renewable energy technologies". Available from: http://landartgenerator.org/LAGI-FieldGuideRenewableEnergy-ed1.pdf [Cited 22 Oct 2014]*

3. *Herzog, A. V., Lipman, T. E. and Kammen, D. M., 2001." Renewable energy sources". A report publised by encyclopedia of life support systems. Available from: http://rael.berkeley.edu/sites/default/files/old-site-files/2001/Herzog-Lipman-Kammen-RenewableEnergy-2001.pdf [Cited 22 Jan 2015]*

4. *Gatte, M. T. and Kadhim, R. A., 2012. "Hydro power" . InTech, open excess chapter. Available from: http://cdn.intechopen.com/pdfs-wm/40550.pdf [Cited 22 Jan 2015]*

5. *Dilip Singh, D., 2009. "Micro Hydro Power". Resource assessment handbook. Available from http://recap.apctt.org/Docs/MicroHydro.pdf [Cited 22 Jan*

*2015]*

6. *Khattak, N., Hassnain, S. R., Shah, S. W. and Mutlib, A., 2006. "Identification and Removal of Barriers for Renewable Energy Technologies in Pakistan". International confernerce on emerging technologies (ICET '06), pp. 397-402.*

7. *Hansen, R. D. " Waterwheels" Available from: http://www.waterhistory.org/histories/waterwheels/waterwheels.pdf [Cited 22 Jan 2015]*

8. *Jones, Z.,2005, "Domestic electricity generation using waterwheels on moored barge". Maters thesis, School of the Built Ennvironment, Heriot-Watt University, Edinburgh, Scotland.*

9. *Lewis, B. J., Cimbala, J. M. and Wouden, A. M., 2014. "Major historical developments in the design of waterwheels and Francis hydroturbines". IOP Conf. series: Earth and Environmental science 22 (2013) doi:10.1088/1755-1315/22/1/012020*

10. *Reynolds, T. S., 1983. "Stronger than a hundred men". J. Hopkins University Press, Baltimore & London.*

11. *Khurmi, R. S., 1987. Hydraulics, Fluid Mechanics And Hydraulic Machines. Chand (S.) & Co Ltd , India. 1987.*

12. *Denny, M., 2004. "The efficiency of overshot and undershot waterwheels" Eur. J. Phys: 25(2) 193–202.*

13. *S. R. Turnock, G. Muller, S. Denchfield, S. Hindley, R. Shelmerdine, and S. Stevens, "Development of a floating tidal energy system suitable for use in shallow water."*

14. *Key Facts, "Irrigation system in pakistan". Available from: http://waterinfo.net.pk/sites/default/files/knowledge/Irrigation%20System%20in%20Pakistan.pdf [Cited 20 Oct 2014].*