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Numerical analysis of low-tech overshot water wheel for off grid purpose

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Abstract. The rural areas of Nepal comprise of many rivers and rivulets which is not properly utilized till yet. In Nepal, the focus is set on overshot waterwheel due to its applicability in low discharge and low head sites with high efficiency. This paper presents the numerical analysis of a low-tech overshot wheel. Simulation of overshot wheel is done at flow rate, and horizontal distance and vertical clearance of the inlet canal. It is found that the water wheel generates higher power at the condition when the flow rate is 25 kg/s, horizontal distance between chute and wheel is 20 cm and the vertical clearance is 2 cm.

1. Introduction

Water wheels are one of the oldest hydraulic machines known to man and have been used since ancient period. Then, water wheels were built of wood and, since the difference between potential and kinetic energy was unclear, the efficiencies were not very high. With the development of hydraulic engineering, and with new materials, the shape, power output and efficiency of water wheels improved substantially [1]. On reviewing the technology behind the power generation of water wheels, the design is dominated by the requirement for a geometry which would minimize losses and retain the water as much as possible. Reports of experimental investigations on the efficiencies of overshot and undershot wheels can be found in literatures. Well-designed water wheels can reach efficiencies of 71 (undershot) to 85% (overshot) [2]. The British engineer John Smeaton was the first to determine the efficiency of water wheels using a series of model tests in 1759. He found that over shot wheels had efficiencies of more than 60%, whereas undershot wheels only reached 30%. The development of hydraulic engineering in combination with a new material – wrought iron, which was much stronger and allowed hydraulically more favourable shapes - resulted in a further evolutionary step of water wheels into rather efficient energy converters for very low heads. During the industrial revolution and in the 19th and early 20th Century, water wheels were subsequently important hydraulic energy converters [3].

Water wheels were also used as mechanical power sources for flour and mineral mills, textile and tool making machines, wire drawing and hammer works, oil mills or water supplies, to generate electricity and for other purposes. The main reasons for the use of water wheels were their comparatively low costs compared with steam engines, and reportedly high efficiencies for a wide range of flow rates, where water wheels compared favourably with turbines [4].

In order to be able to utilize the head differences from 0.5 to around 12m, three basic types of water wheels were developed. Most wheels employed only the potential energy of the water. Three forms of waterwheel namely undershot, overshot and breast-shot are commonly defined along with their working principles. In overshot waterwheel, water enters from above the wheel, which rotates in the opposite directions to undershot and middle-shot waterwheels. These are predominantly driven by the water's potential, resulting from gravity [5].

Figure 1 Overshot wheel fabricated by Lukas Geb and Johannes Eisner in Germany [6]

Comparison of hydraulic turbines with waterwheels

Generally, the most used turbines are impulse and reaction turbine. The turbines like Pelton, Francis and Kaplan are mostly used in world scenario for hydropower technology. Such hydraulic turbines work in different head conditions from low to high. In reaction turbine, it induces impulsive force that finally makes the turbine rotate. In reaction turbine, working fluid comes to the turbine under immense pressure and the energy is extracted by the turbine blades from the working fluid. But in waterwheel, water hits the surface tangentially, beneath or around the same height of shroud. According to its surface hitting phenomena, waterwheel is categorized into three types i.e. Overshot, Undershot and Breast-shot waterwheel respectively.

Study Site

The installed site is in Ghattekulo, Kushadevi 10km away from the Kathmandu university. The overshot water wheel consists of 12 modules chamber, outer diameter of the waterwheel is 1.1m and the width of each bucket is 30cm. The waterwheel is responsible for transforming the gravitational energy to kinetic energy and finally to electrical energy. Chute is made up of galvanized steel. For the site, the slope of chute is 1^0 and the vertical level was chosen to be 2-4 cm above the impact paddle edges of the water wheel, the velocity of water flowing through the chute is around 2.11 m/s and the flow rate is measured to be 80 l/s during the monsoon season of Nepal. However, the turbine was operated at flow rates of 15 kg/s, 20 kg/s, 25 kg/s and 33 kg/s during its operation. The available head in the site was 1.70 m. The location of the installation of waterwheel is illustrated in Figure 2 where 1, 2 and 3 are the locations for the installation of the water wheel. In each location the water was diverted from the canal to the chute. The flow velocity of water was calculated by the following equation,

$$Q = A_{canal} * V_{flow\ of\ water} \qquad (1)$$

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Figure 2 Locations for installation of overshot waterwheel [7]

2. Design Study

Operating Principle

Overshot wheel is a type of waterwheel that has vertical wheel with horizontal axle. In this type of waterwheel, the water hits near the top of wheel i.e. tangentially so that it runs away from head race where the driving surfaces of the overshot wheel is chambers or buckets. It is generally used with low head and low flow rate conditions and has highest efficiency than the other two types of the waterwheel i.e. undershot and breast-shot waterwheel. The overshot waterwheel is able to exploit the lowest flow rate with the highest efficiency up to 85% when properly designed.

The impulse and gravity is the main factor for accounting the operating principle of the wheel. Firstly, the gravitational energy or potential energy is converted to kinetic energy due to moving velocity of water. Subsequently, the gravitational energy of the water inside the buckets generates torque. Finally, the water is discharged from the tail race.

Hydraulic Design

Water wheels are designed on the basis of available head and flow rate. To design the overshot wheel, the diameter of the wheel is determined by the head difference i.e. (head race – tail race). It has to be decided whether the wheel will be operated with free or regulated inflow (i.e. constant or variable speed) since this affects the available head. The inflow detail with or without a sluice gate has to be designed so that the design flow volume can be guided into the wheel.

The design started with an idealized overshot waterwheel model, which served to introduce notation and some basic concepts. As shown in Figure 4, 12 triangular buckets are attached to the rim of a wheel. Each bucket is free to swivel about a horizontal axis. The buckets are filled with water, which is assumed to drop vertically from a flume. The filled buckets cause the waterwheel to rotate. At a 'spill angle' θ_1 near the rim of the wheel is a baffle that causes the buckets to shed water, otherwise no water will be spilled. It is assumed that the wheel is frictionless and effect of the millstone is represented by a constant load torque G_L.

The wheel has been constructed so that torque is applied solely from the gravitational potential energy of the water, and not from its momentum. The more realistic model in what follows will include water momentum, as well as permit water spillage and allow for friction, and other such unavoidable realities. It is assumed that the buckets at an angle θ, where $0 < \theta \leq \theta_1$, are filled with water and that all the others are empty. There are n buckets each occupying an angle θ around the rim, so that $n\Delta\theta = 2\pi$. The mass of water in each bucket is $\Delta m = \rho f \Delta t$, where ρ is the water density (kg m^{-3}), f is the flow rate (m^3 s^{-1}) and Δt is the time interval over which water fills the bucket. We can obtain this from $\omega\Delta t = \Delta\theta$, where ω is waterwheel angular speed, so that:

$$\Delta \mathrm{m} = \frac{\rho f}{\omega} \Delta \theta \tag{2}$$

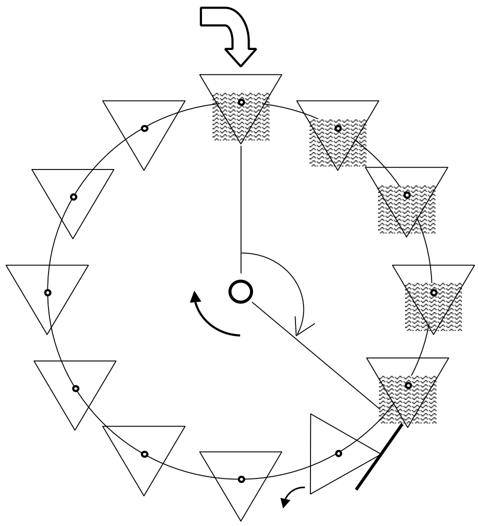


Figure 3 Idealized overshot waterwheels powered by gravitational potential energy

In Figure 4, water drops vertically into buckets, and remains there until tipped out at angle θ_1. The possibility of water overflowing is ignored due to slow rotation rate, or due to fast rotation (centrifugal force). The torque applied about the waterwheel axle by the weight of water is $\Delta \mathrm{G} = \Delta \mathrm{mgR} \sin(\theta_1)$ per bucket, where *R* is the wheel radius and θ is the location of the filled bucket. For large *n* we can calculate the total torque as follows:

$$G \approx \frac{\rho g f R}{\omega} \int_0^{\theta_1} d\theta \sin(\theta) = \frac{\rho g f R}{\omega} [1 - \cos(\theta_1)] \tag{3}$$

Assuming that *n* is large, the torque (opposing that of equation (3)) arising from the buckets being emptied is ignored when they reach θ_1. For this idealized water wheel, the equation of motion is:

$$I\dot{\omega} = \mathrm{G} - G_L \tag{4}$$

where *I* is the moment of inertia of the wheel plus water, and where $\dot{\omega} = \frac{d\omega}{dt}$.The equation (4) is not solved, but it is noted that there is a stable state for this system with angular speed

$$\varpi = \rho g f R / G_L [1 - \cos(\theta_1)] \tag{5}$$

as is readily seen from (3) and (4).

The efficiency of waterwheel is calculated as follows. The energy input by each bucketful of water is $\Delta \mathrm{E} = 2\Delta \mathrm{mgR}$ and the corresponding power is

$$\Delta P_{in} = \Delta E_{in} \frac{\omega}{\theta_1} \tag{6}$$

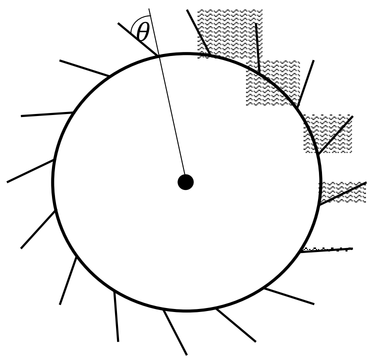


Figure 4 Overshot waterwheel with canted vanes (bucket separation)

In the figure 6, as the bucket angle increases ∅, water is retained for longer, increasing the torque. Assuming that the wheel rotates at the constant steady-state rate ϖ. The total input power is: $P_{in} = \frac{\theta_1}{2\pi} n\Delta P_{in} = 2\rho g f R$.

Useful output power is $P_{out} = \varpi G_L$ and so waterwheel efficiency is found to be :

$$\varepsilon \equiv \frac{P_{out}}{P_{in}} = \sin(0.5\theta_1) \quad (7)$$

So the efficiency of this idealized waterwheel is independent of all the parameters except the spill angle. This is a consequence partly of our idealizations and partly of our assumption that the wheel is powered solely by gravity, i.e. by the weight of water alone, and not its momentum. Efficiency can be 100% if the spill angle is $\theta_1 = \pi$, so that the water contributes to torque until it is at the bottom of the wheel. For practical waterwheels, this is difficult to achieve, so the efficiency is reduced.

Concept of modularity in overshot wheel

The aim of the modularity is to find an easy concept to construct a water wheel rim. To be able to open the water wheel implementation to the majority of the Nepali, the costs have to be low, the design must by robust against tolerances in production and mistreatment, the maintenance in case of damage should be easily manageable and it should not be required to have a special knowledge or high-tech machines to convert the concept into reality. Additionally, it would be an advantage, if transport and assembly can be keep simple so that the water wheel can be installed in remote areas even without road connection or special equipment. All the mentioned needs occur due to the circumstances that exist in Nepal. To meet these challenges, the idea is to realize a modular design. Meaning, the rim of the water wheel should be assembled from many similar parts (cells, modules). By varying the number of cells used for one water wheel, it should be possible to optimize the water wheels for different heights of fall and volume flowrates of water without redesigning the parts every time. Hereby, a modular concept allows that the single parts can be produced in an easy way and the manufacturer can use the learnt skills more often what accelerates the total production process. The water wheel assembly based on single modules enables a very easy transportation to the site and submits a preparation of the segments in a workshop such that only little work has to be done to finalize the water wheel on site. It gets clear that the modular design is a key to meet all the occurring needs for water wheel construction in Nepal. A concept starting with low heights of fall of $H = 1.0\ m$ enables the use of the little gravitational power potential that is available at many sites in Nepal [6].

Performance Characteristic

Although a large number of overshot water wheels were in operation in the last century, only three series of tests where the efficiencies were determined were performed. Most of the test results were never published in hydraulic engineering textbooks or journals and are only available in not widely known articles and reports. The efficiency against flow rate curve displays one of the main characteristics of any turbine. Figure 6 shows a typical efficiency curve from one the reported tests. The efficiencies reach around 85% even for very small ratios of Q / Q_{max} of 0.3, and remain at this level up to $Q = Q_{max}$, so that the water wheel (when well designed) can be regarded as a rather efficient energy converter with the additional advantage of having a broad performance band width [4].

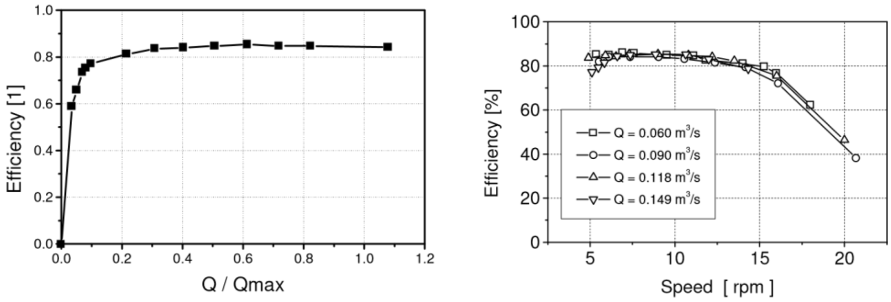


Figure5 Efficiency curves for an overshot water wheel [4]

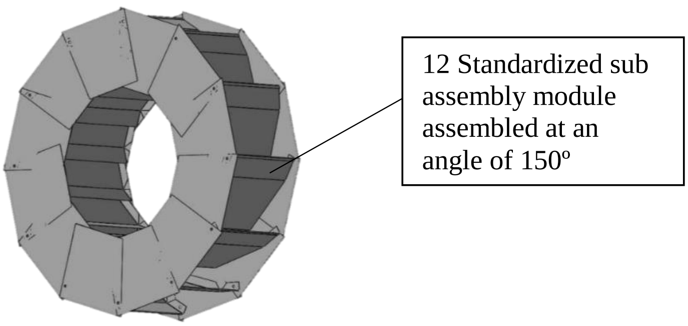
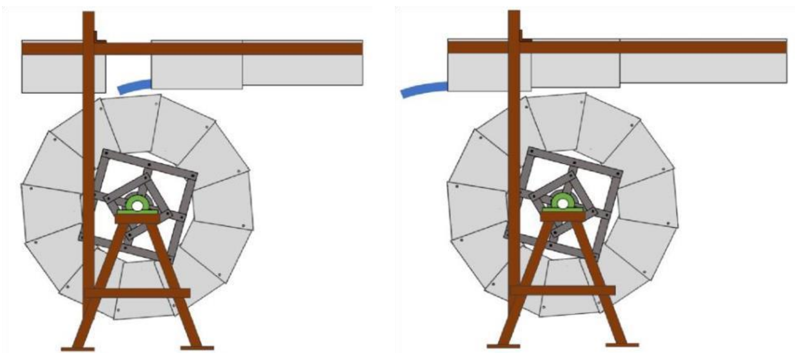


Figure6 CAD model of Assembled chamber [own illustration]



(a) (b)

Figure 7 (a) Turbine is loaded with water (b) Water is guided beyond the turbine [6]

3. Numerical Model

Fluid Domain

Two different fluid domains were inserted, rotating and stationary. As multiphase domain was to be created, fluid and particle definitions was inserted with fluid 1 being water. The domain motion for rotating domain was changed to rotating type with angular velocity set to 20 rpm in anticlockwise direction. Different boundaries were inserted in the rotating domain. The domain motion for rotating domain was given rotating with reference to Z axis. The buoyant conditions were applied where taken reference to y axis is only take as 9.8 m/s^2. Inlet was defined with mass flow rates and the outlet was defined with the atmospheric pressure. At interface, frame change was set to transient rotor stator with pitch ratio value of 1. Figure 9 shows the set up in CFX-Pre.

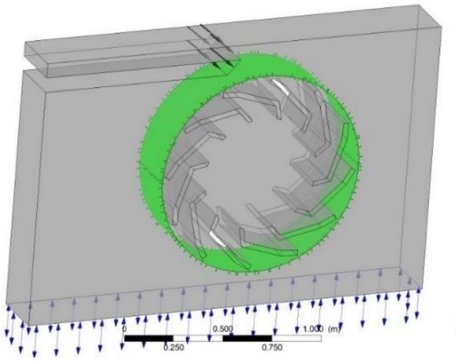


Figure 8 Setup of stationary and rotating domain

Mesh

The meshing was done using in-built ANSYS meshing with unstructured topology. The rotating domain of each of the turbine model was meshed with element size 0.001 m whereas the stationary domain was meshed with element size 0.002 m. The fine mesh with refining and face meshing resulted in 632140 number of nodes in the stationary domain and 1365124 number of nodes in the rotating domain.

Boundary Conditions

The inlet boundary condition for the stationary domain was set to bulk mass flow rate of 33 kg/s and 25 kg/s with flow direction normal to boundary condition. Similarly, outlet condition was set to static pressure where analysis type was transient blade row, turbulence model used was k-Epsilon. As shown in Figure 10, different conditions of horizontal distance (a) and vertical clearance (b) were varied to analyse the case to obtain the optimal parameter for efficient results.

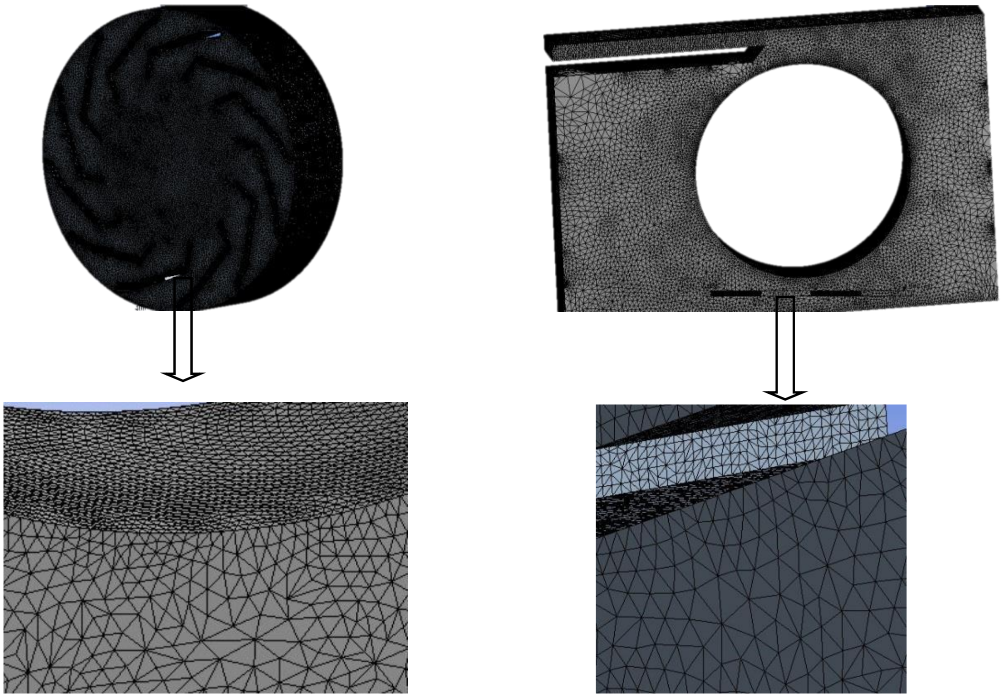
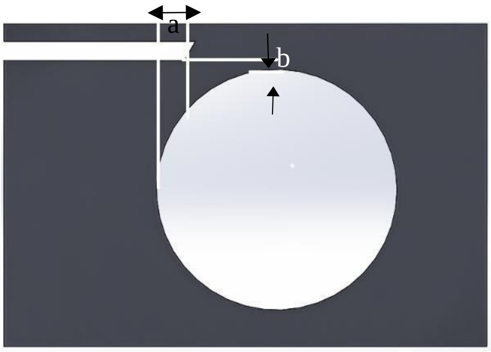


Figure 9 Meshing of rotating and stationary domain



Cases of Stationary Domain

a	b
	2cm
	4cm
20cm	2cm
	4cm
25cm	2cm
	4cm
30cm	2cm
	4cm

Figure 10 Parameters of stationary domain

4. Result and Discussions

The results of analysis of water wheel when compared to the installed water wheel in Panauti site has similar fluid flow pattern as shown in Figure 11. When fluid flows from chute it strikes and pass through the bucket which results in the rotation of the wheel.

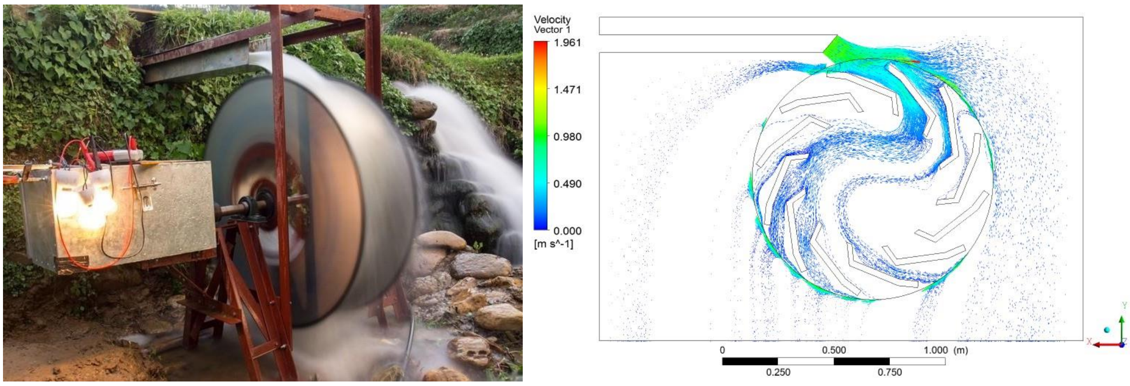


Figure 11 Comparison of the actual flow pattern in the installed waterwheel with the result of CFD

Effect of the horizontal distance(a)

The horizontal distance was taken at 5 cm, 10 cm, 15 cm, 20 cm, 25 cm and 30 cm and torque were calculated for these conditions keeping discharge 33kg/s, rpm 45rpm and vertical distance at 2cm.The maximum torque was obtained for 20 cm condition i.e. 14.5 Nm.

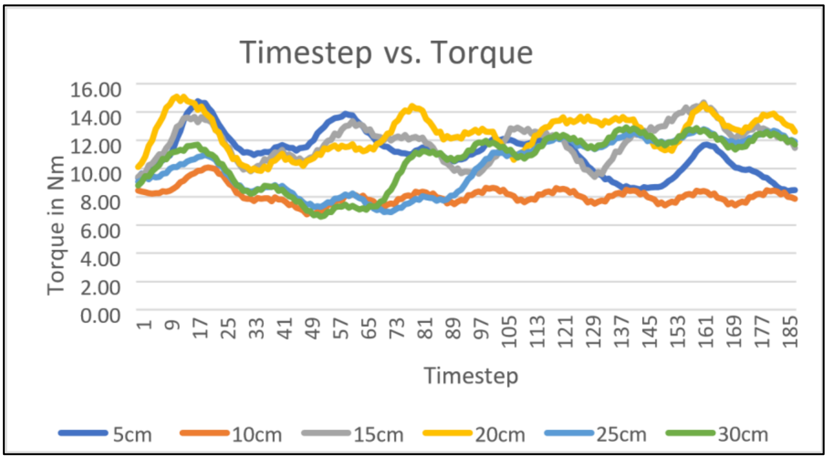


Figure 12 Torque vs. Time Graph when horizontal distance between chute and wheel outer edge were varied

Effect of the discharge at variable horizontal distances

The discharge plays an important role in obtaining efficient torque. With increase in discharge of fluid, torque gets increased but after a point though discharge get increased, torque starts decreasing. The maximum average torque was obtained when discharge was 25 kg/s and horizontal distance was 25 cm.

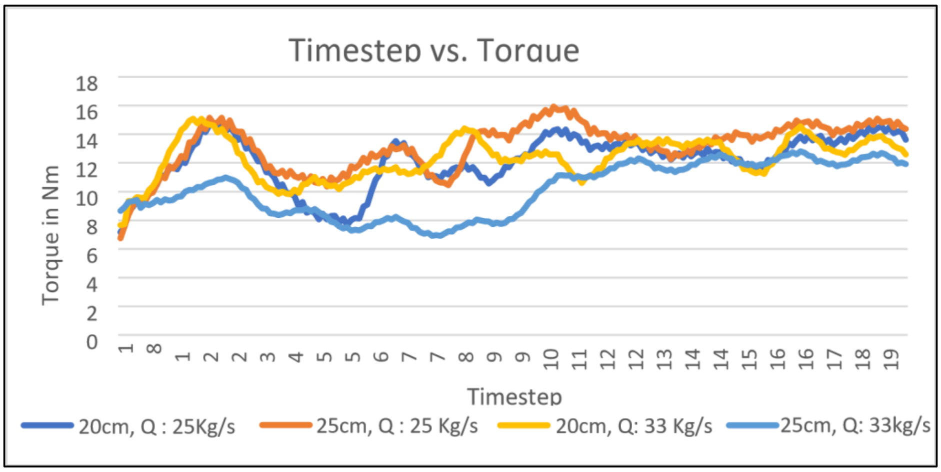


Figure 13 Timestep vs. Torque graph when horizontal distance and discharge were varied

Effect of the vertical distance (b)

The variation in vertical clearance between wheel outer edge and chute results in variation of the output torque. When vertical clearance between wheel and chute were varied at constant discharge and horizontal distance, the change in torque were obtained.

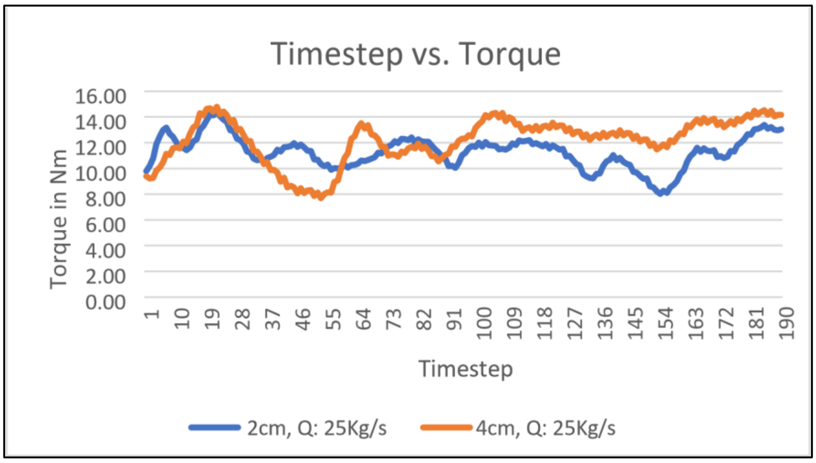


Figure 14 Timestep vs. Torque graph when vertical clearances were varied

5. Conclusion

From the simulations results of different working condition, it was found that the overshot waterwheel for this case works best at the condition of 25 kg/s flow rate, horizontal clearance of 20 cm and vertical clearance of 2 cm. The chute with and without angle was also checked in the all working conditions and was found that water strikes abundantly in the overshot waterwheel when the chute was varied with the angle. So it is recommended that the chute angle should be at around 45 degrees to exploit the maximum use of striking water into the bucket of overshot waterwheel considering the vertical clearance of 2 cm between chute(canal) and overshot waterwheel.

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