

Design and Development of a Vortex Turbine for the Hilly Regions of Bangladesh

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ABSTRACT

In the modern world, the days of fossil fuel-based electricity are numbered. In addition, the need for cleaner, greener, and more efficient energy is on the rise. Sustainable energy technology is needed to meet the demand for an environmentally friendly power source that provides consistent power. Small hydropower is an effective alternative source of energy in mountainous places in many parts of the world. Small hydro-powers reliably produce low-cost and clean power. The study was carried out on a gravitational vortex water turbine, a small hydropower source. It works with very little impact on the environment. Here, gravity-flow water moves turbine blades which are coupled with a generator via a shaft. The turbine used in this study was an impulse turbine. To enhance the efficiency of the turbine, different blade parameters were studied along with different design parameters. By modifying the blade angle and enhancing the blade surface area by adding baffle plates, a more rotational speed can be achieved. It was found that the construction containing 5 blades and 44° blade angle produced an efficiency of 82% for the curved blade profile. As a result, increased electricity production is achieved, and we got an estimated turbine output power of 6.91 KW. This study has the potential of changing the power scenario of the Chittagong Hill Tracts for the foreseeable future.

Keywords: *Gravitational vortex turbine, hydropower, turbine blade.*

1. INTRODUCTION

The days of fossil-fuel-based electricity are declining in the modern world, and the need for cleaner, greener, and more efficient energy is increasing. To meet the energy demand, and environmentally friendly power source that offers consistent power is required. Small hydropower can be a valuable green energy source for hilly regions all over the world. In this paper, a study has been conducted on the design and optimization of a gravitational vortex water turbine, a small hydropower source for Chittagong hill tracts of Bangladesh. A research article by Razan et al. (2012) studies the potential of micro hydro-power and the parameters that need to be considered in Bangladesh [1]. Potential small hydro-power sites were identified by BPDB, BWDB, and IFRD of BCSIR that are shown in Table 1. The study shows that Bangladesh is mostly a flat country where most of the hydro-potential resides in the Chittagong Hill Tracts.

Table 1. Potential small hydro sites identified by BPDB and BWDB [1]

District	Name	Potential of Electrical energy (kW)
Chittagong	Foy's lake	4
Chittagong	Chotokumira	15
Chittagong	Hingulichara	12
Chittagong Hill Track	Sealock	81
Chittagong	Lungichara	10
Chittagong	Budiachara	10

A *gravitational* vortex water turbine follows the principle of an impulse turbine, and it employs gravity to cause water to flow downstream. Water is flown through a straight path into a round basin where a water vortex is created and a pre-installed turbine collects the rotational energy from this vortex and it gets converted into electrical energy [2]. Figure 1 shows the main concept of the turbine where the vortex is generated due to the shape of the basin and hence electricity is produced.

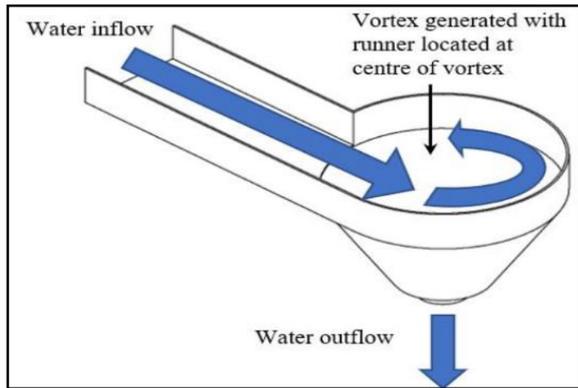


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The primary purpose of this research is to design an efficient vortex turbine by adjusting several turbine blade parameters such as blade material, blade angle, and the addition of baffle plates. Dhakal et al. (2015) performed their study on different basin shapes which mainly includes cylindrical and conical shapes with ideal runner placement. According to their study, the conical basin was found to be most efficient because, in a cylindrical shape basin, the vortex generation near the orifice gradually weakened [3]. In turbines, blades play the most important role when it comes to energy conversion. Rahman et al. (2017) studied that, the maximum efficiency obtained by the researchers is approximately 30% while the commercial companies claimed about 50% of efficiency with 500 W to 20 kW of power generated [4]. So, efficiency is crucial in vortex turbines. Dhakal et al. (2017) performed their research on different turbine blade profiles and the curved blade profile was found to be the most efficient (82.4%) among them [5]. Sritram et al. (2015) focused on distinct turbine materials to observe electricity production efficiency. A turbine blade constructed of aluminum (34.79%) was found to be the most efficient because the weight of the aluminum turbine was lighter than that of the steel turbine, it could move at the highest speed for a shorter time than the steel turbine [6]. Bajracharya et al. (2020) studied the effect of blade angle, height ratio, and blade number. In this study, it was discovered that blades should be curved when

viewed from the top only with blade angles between 50° and 60°, implying that blades should be curved along the horizontal plane. Height ratio is the ratio between runner height and basin height. Since the basin height is constant, only runner height can be increased. And when runner height increases, the surface area of the blade also increases, and hence water contact with the blade surface increases. As a result, efficiency increases. In this study, the best Runner height to basin height ratio was found to be 0.31–0.32. This investigation also discovered that the runner with 5 blades is the most efficient [7]. Sritram and Suntivarakorn (2019) also studied the turbine blade numbers effect. They also found out that, runners with five blades were the most effective [8]. Kayastha et al. (2019) did their research to best runner position, and it was found that the torque increases with the runner position from the top of the basin. But because of the runner design, it must be placed at the core of the vortex for better power generation [9].



Figure 2 Attribution: Adapted from (Siddique et al., 2021, Figure 8) © 2021 by the authors. License MDPI, Basel, Switzerland. Distributed under the terms and conditions of Creative Commons Attribution 4.0 International License

Energy demand continues to rise, particularly in emerging countries like ours. But during this unsteady time, according to British Petroleum (BP) statistical report 2021, The COVID-19 pandemic had a dramatic impact on energy markets, with both primary energy and carbon emissions falling at their fastest rates since the Second World War. It shows that Primary energy consumption fell by 4.5% in 2020 which is the largest decline since 1945 [10]. Luckily Wind, solar, and hydroelectricity all grew despite the fall in overall energy demand. So, this is the perfect time to create awareness about using renewable energy. Among all these renewable energy sources, hydropower is the most

economical abounded energy source [4], but unfortunately, hydropower output grew by 1% only where China was the largest individual contributor. Countries like Bangladesh that are full of rivers canals can use these sources to generate more hydropower. The most well-known technique of generating energy from hydropower is to build an artificial lake and then expand it into a huge dam along a river’s course. The environmental consequences of this sort of hydroelectric facility are considerable, necessitating a re-evaluation of the project. However, as public awareness of this consequence and renewable energy sources has grown, demand for small-scale hydraulic power generation using a water turbine has grown, allowing for the use of previously underutilized common rivers or waterways with low heads and low flow rates. Hence to harvest energy from low headwater sources, the concept of Gravitational Water Vortex Power Plant was enacted.

2. METHODOLOGY

2.1 Related Codes and Standards

A guidebook published by European Small Hydro-power Association - ESHA (2004) is the golden standard for any hydro-power plant set up in the EU and it echoes the EU’s strict rules to ensure a better quality of life and minimize harm to the environment. A guideline by Pushpa Chitrakar (2015) focuses on hydrology and which regions of Nepal are best suited for a micro-hydro project. The process used is called Medium Irrigation Project Method. The month of April is taken as standard and according to the climatological data, streamflow records, topographical map, groundwater data, wading, etc., hydrological data is achieved which is used for further developing the micro-hydro project. Mean monthly flow is determined which gives a clear idea of the timeline during which the hydro plant can operate at its peak.

2.2 Small Hydro Resources in Bangladesh

Bangladesh has a largely under-utilized hydroelectric supply in terms of micro-hydropower as shown in Figure 2. Karnafuli hydro-power facility with a capacity of 230 MW, is the country’s sole source of hydro-power [11]. On the banks of the Matamuhurri river, a micro-hydropower plant with a capacity of 10 kW has been installed. This plant provides electricity to 140 homes in isolated Banderban mountainous areas. Another proposal has been developed by Wazed et al. (2008) to utilize the flow of the Sangu River; this facility is expected to produce 140 MW [12]. Shahid (2015) dives into the study of different challenges that the country faces when it comes to hydro-power [13].

2.3 Design Analysis

The solid modeling of the prototype was prepared using SOLID-EDGE software. The final arrangement of the design is shown in Figure 7. The main system consists of an incoming channel from an open river stream with an angle to support the initial speed required for the gravity flow. A notch increases the velocity of flow as the channel area decreases. The notch is then connected to a conical basin where the potential and kinetic energy of the speeding waters is converted into kinetic energy as the waterfalls into the conical basin. A five-legged impulse turbine system collects the energy, and it is then transferred by a shaft. The details of the impulse turbine are shown in Figure 3.

2.4 Design Parameters

2.4.1 Basin parameters

The parameters shown in Table 2 were crucial for designing the conical basin and these parameters were used for designing the basin shown in Figure 6.

Table 2. Geometrical parameters of the basin

Parameter	Value	Unit
Gate angle	15	degree
Notch angle	10	degree
Notch inlet width	0.15	m
Cone angle	67	degree
Channel height	0.18	m
Channel width	0.144	m

2.4.2 Blade parameters

The selection of proper blade parameters is important for extracting maximum efficiency from incoming fluid flow. Below value of parameters are shown in Table 3 and was used for designing turbine blade profiles.

Table 3. Geometrical parameters of blade

Parameter	Value	Unit
Curved blade angle	44	degree
Blade number	5	none

2.4.3 Shaft parameters

These parameters shown in Table 4 were used to design the proper shaft for our study. The designed shaft is shown in Figure 5 and calculations are given in the validation study section.

Table 4. Geometrical parameters of the basin

Parameter	Value	Unit
Shaft outer diameter	18.415	mm
Shaft inner diameter	13.081	mm
Shaft length	286	mm

2.5 Turbine

In previous studies, observation of efficiency was conducted with a straight blade, twisted blade, and curved blade. Among these blades, the curved blade was found to be the most efficient and delivered more power [5]. Moreover, using baffle plates with the turbine blade can produce high torque as experimented by previous studies [8]. We decided to design a turbine with a curved blade and along with baffle plates as shown in Figure3 and Figure4. Previous studies also suggested that a gravitational water vortex turbine with 5 blades yielded more power compared to a turbine with more or fewer blade numbers [8][7]. Aluminum is selected as the turbine material because of its lighter mass, and it can spend less time revolving at a higher speed.

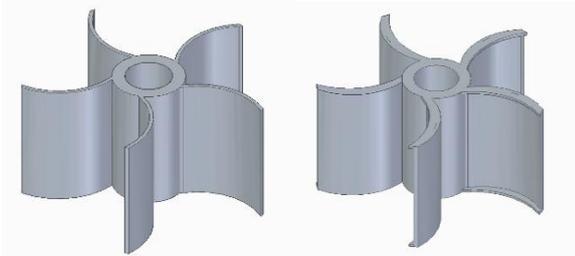


Figure 3: Curved blade

Figure 4: Curved blade with baffle plates

2.6 Shaft

A hollow shaft made of Aluminum was studied to be attached to the turbine [6] as shown in Figure5. Because the hollow shaft generates a lower polar moment of inertia compared to a rigid shaft thus increases torque and speed.



Figure 5 Aluminium hollow shaft

2.7 Basin Selection

In the previous studies, it was found that, for the same inlet and outlet condition, the conical basin delivered more power and was more efficient than the cylindrical basin [14]. That is why a conical-shaped basin was decided to be mounted in our study illustrated in Figure 6.

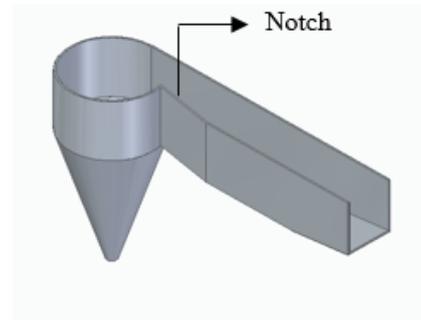


Figure 6 Conical basin

2.8 Final Assembly Design

Figure 7 is the complete assembly design of our system. Water is flown through the canal and a vortex is generated because of the conical basin. The turbine blade is connected to the shaft which is connected to the generator via a belt-pulley system.

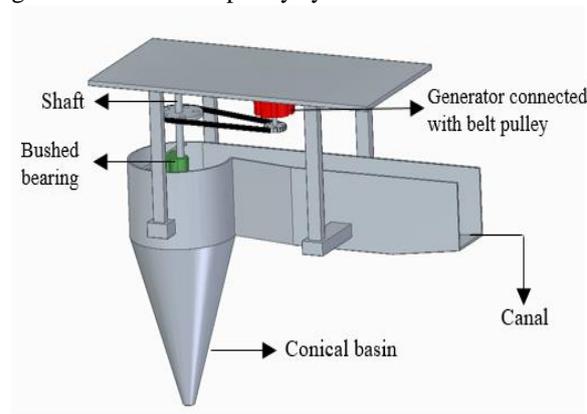


Figure 7 The total assembly of the system

3. PERFORMANCE ANALYSIS

The performance analysis was done on a theoretical basis and a mathematical model was developed in a Google spreadsheet.

3.1 Related Formulas

The following equations are obtained from the book “Basic Fluid Mechanics and Hydraulic Machines” (Zoeb Husain, 2008) [15]

$$\text{Actual velocity, } v = \frac{Q}{A} = \frac{4Q}{\pi d^2} \quad (1)$$

Here,
 Q = Experimental flow rate, d = Diameter of the nozzle

$$\text{Peripheral velocity, } U = \frac{\pi DN}{60} \quad (2)$$

Here,
 U = Peripheral velocity, D = Outer diameter of the turbine. N = Rotational speed.

$$\text{Inlet hydraulic power, } P_i = \gamma QH \quad (3)$$

Here,
 Q = Experimental flow rate, H = Head available at the nozzle, γ = Specific weight of water

$$\text{Turbine output power [16], } P_o = n_\tau QH g \rho \quad (4)$$

Here,
 n_τ = Hydraulic efficiency, ρ = Density of water

Hydraulic efficiency,

$$n_\tau = \frac{2 \cdot U \cdot (V_1 - U) \cdot (1 + \cos \beta)}{V_1^2} \quad (5)$$

Here,
 U = Peripheral velocity of the turbine, V_1 = Absolute velocity of the jet before striking the blades, β = Turbine blade angle.

3.2 Validation study

Since we couldn't conduct any field test due to COVID-19, we had to rely on assumptions to get the values of the head, flow rate, and RPM. A gravitational vortex water turbine's head can be as low as between 0.7m-3m. Since we are assuming, we chose ahead of 0.5m, and luckily at our university campus, a similar type of experiment went on where for a head of 0.5m a flow rate of 1.72 liter/sec was achieved. We chose an initial

RPM of 210 since in most of the previous studies for similar head RPM of 180-250 were seen.

3.2.1 Blade number

Since we couldn't conduct any physical experiment, we had to rely on the works of previous authors for the selection of Blade number. A study by P. Sritram and R. Suntiwarakorn on the effect of blade number on free vortex water turbine showed that the turbine with five blades yielded the maximum torque [8]. It turned out that a turbine with five blades yielded the maximum torque. Here torque increased 8.06% when the experiment was conducted with 5 blades instead of 4 blades.

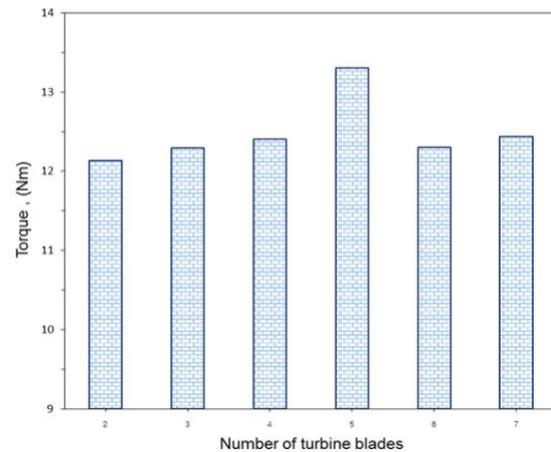


Figure 8 Attribution: Adapted from (P. Sritram and R. Suntiwarakorn 2019 IOP Conf. Ser.: Earth Environ. Sci. 257 012040) Distributed under the terms and conditions of Creative Commons Attribution 3.0 International License

Also, Payambarpour et al. (2019) worked with blade numbers two, three, five, eight, ten to find out the Blade Number Effect on Hydraulic Performance of In-Pipe Hydro Savonius Turbine keeping the same flow rate through all the turbines and it was found that five-bladed turbine yielded the maximum efficiency of 28.15% [17]. Here efficiency increased to a whopping 40.05% when blade number increased from 3 to 5.

Table 5. Efficiencies with blade number [17]

Blade number	Efficiency %
2	14.15
3	20.10
5	28.15
8	26.41
10	24.66

Moreover, Bajracharya et al. (2020) worked on the Effects of Geometrical Parameters in Gravitational Water

Vortex Turbines with Conical Basin and experimented to find out the perfect blade number [7]. They worked with blade number three, four, five, six and kept all the parameters the same. They found that 5 bladed turbine was the most efficient. Finally, the power coefficient increased to 4% when the blade number increased from 4 to 5.

Table 6. Efficiencies with blade number [7]

Blade number	Efficiency %
3	43.25
4	46.03
5	48.05
6	46.23

Since in all these studies, experimenting with different blade numbers while keeping all the other parameters the same, five-bladed turbine came out to be the most efficient we can expect to have better results with five-bladed turbines.

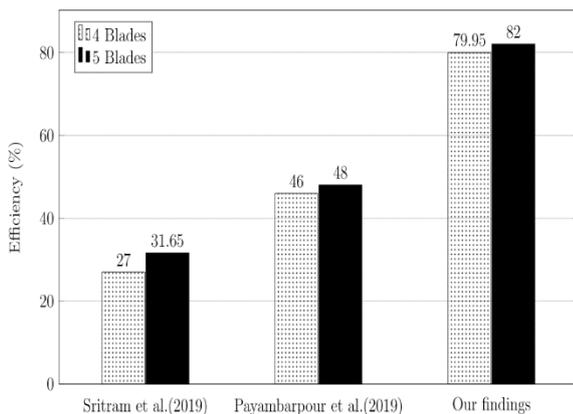


Figure 9 Graphical representation of efficiencies

Now in the first and third experiments, efficiency increased 8.06% and 4% respectively. So, we assumed an increment in efficiency when using 5 blades instead of 4. For theoretical analysis, we assumed multiple parameters where we used rpm of 210. So, for our calculation, an increment of 4% in this rpm due to using 5 bladed turbines which resulted in an efficiency of 82% whereas for 4 bladed turbine we got an efficiency of 79.95%. We can see the graphical representation in Figure 9.

3.2.2 Blade Angle

A proper blade angle, as well as a blade profile (curvature), is required for any turbine to get the maximum energy from the fluid. In this research, we worked with a turbine that has 5 blades which are curved at 44°. Figure 10 and Figure 11 show the designed blade profile for this study. To calculate the efficiency, we

assumed several parameters and with this blade curvature, an efficiency of 82% was found. Dahal et al. (2019) performed their experimental study for a blade angle of 55° for which they found their maximum efficiency [18]. Moreover, Dhakal et al. (2014) worked to test the runner and the conical basin for the vortex turbine and found maximum efficiency for a blade angle of 44°.

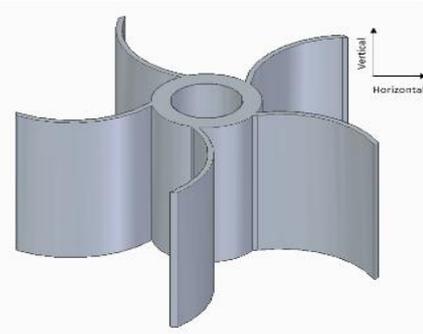


Figure 10 Curved blade (horizontally)

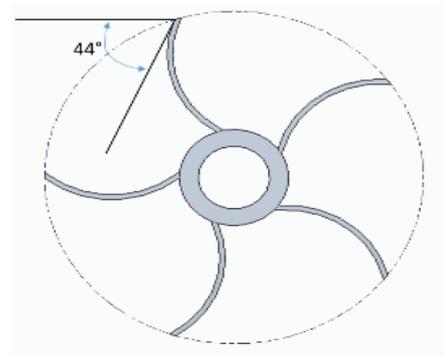


Figure 11 The top view of the angled blade

Now to validate our results, we compared our findings with Bajracharya et al.'s (2020) work on the effects of Geometrical Parameters in Gravitational Water Vortex Turbines with Conical Basin, and in that research, they obtained maximum efficiency for a turbine blade of 53° [7]. A graphical comparison is shown in Figure 12.

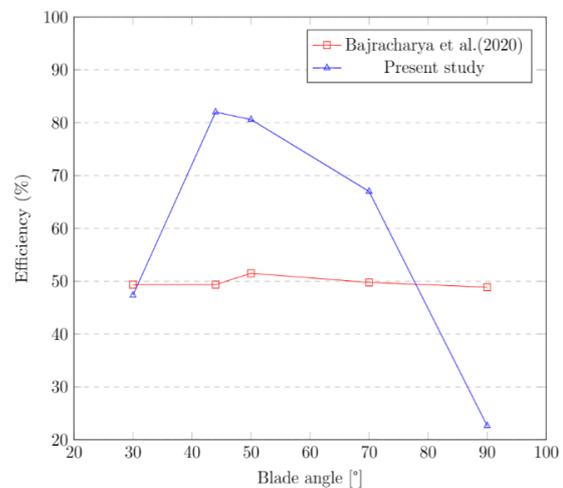


Figure 12 Graphical representation of blade angle vs efficiency

3.2.3 Shaft

The height of our conical basin is 532 mm

So, we assumed our shaft length = (10 mm upper from the center of the top circle of conical basin + 10 mm lower from the center of the conical basin + Height from center of the conical basin to the top center of the conical basin) = $10 + (532/2) + 10 = 286$ mm

Also, the shaft outer diameter is 18.415 mm

Shaft inner diameter 13.081 mm

Now, L/D = Slenderness ratio for shaft

Now,

L/D is less than 27 (standard) (shaft length to diameter ratio) [19]

Polar moment of inertia calculation:

$$(L/D = 286/18.6 = 15.5)$$

Our value is 15.5, which is less than 27.

Now,

Using hollow shaft equations:

$$\begin{aligned} \text{Shaft cross sectional area is, } A_d &= \pi^4 (D^2 - d^2) \\ &= 131.95 \text{ mm}^2 \\ &= 0.00013196 \text{ mm}^2 \end{aligned}$$

$$\text{Volume } V_d = A_d L = 3.774056 \times 10^{-5} \text{ m}^3$$

$$\text{Mass} = \text{Density} \times \text{Volume}$$

Following specifications: Aluminum

$$\text{The density of the shaft is, } \rho = 2710 \text{ kgm}^{-3}$$

$$\text{Mass, } m_p = \rho V_d = 0.10 \text{ kg}$$

Shaft weight,

$$Q_p = m_p g = 1 \text{ kgms}^{-2}$$

From the polar moment of inertia of a hollow and rigid body,

According to the data we get,

$$\text{For hollow shaft, } J = 0.00000008415 \text{ m}^4$$

$$\text{For rigid shaft, } J = 0.0000000113 \text{ m}^4$$

4. CONCLUSION

Gravitational vortex water turbines are economic, off-grid energy solutions because they are easy to manufacture and implement [20]. Most of our study on this turbine was done on a theoretical basis because of the ongoing Coronavirus (COVID-19) pandemic. Fortunately, the design of the prototype along with two blade profiles, namely curved and curved blade with the addition of baffle plates would be performed. For better vortex generation, a conical basin was also designed [21]. We were able to conduct the performance analysis process and validation study with the assistance of proper assumptions and the data from the previous researchers. It was found that an efficiency of 82% can be achieved with a curved blade profile of 44° as well as a turbine output power of 6.91 KW. Furthermore, we analyzed the associated sustainable development goals. This project supports sustainable development goals mainly "Affordable and clean energy" (SDG-7), "Responsible consumption and production" (SDG-12), "Climate action" (SDG-13), these SDGs are very crucial for a sustainable future. As hydropower is a renewable energy technology, it does not emit any harmful elements, unlike conventional power plants. Furthermore, this initiative supports sustainable development agenda which in turn could alleviate poverty, growing inequalities, and in the long run address shrinking resources and natural and human-related disasters [22].

4.1. Future Scope

In the future, further studies can be carried out on the tilted blade angle. Moreover, a multiple stages gravitational vortex water turbine is on the horizon and very few studies are conducted on it. So, the above-mentioned type of turbines can also be studied and used commercially.

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