DOE/EE/15669--T1

DEVELOPMENT OF THE HELICAL REACTION HYDRAULIC TURBINE

Final Technical Report

(DE-FG01-96EE 15669)

Project Period: 7/1/96 - 6/30/98

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

For submission to:
The US Department of Energy, EE-20
1000 Independence Avenue, SW
Washington, DC 20585
Attn: Mr. David Crouch

Prepared by:
Dr. Alexander Gorlov, PI
MIME Department
Northeastern University
Boston, MA 02115

August, 1998

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

SUMMARY

The present report contains the final results obtained during July 1996 - July 1998 under the research project sponsored by the US Department of Energy. This report should be considered in association with our Annual Progress Report submitted to the DOE in July 1997 due to the fact that not all of the intermediate results reflected in the Progress Report have been included in the Final Report. The aim of the project was to build a helical hydraulic turbine prototype and demonstrate its suitability and advantages as a novel apparatus to harness hydropower from ultra low-head rivers and other free water streams such as ocean currents or rivers without dams.

The research objectives of the project are:

- Design, optimization and selection of the hydro foil section for the helical turbine.
- Design of the turbine for demonstration project.
- Construction and testing of the turbine module.
- Assessing test results and determining scale-up feasibility.

As one can see, the research conducted under this project has substantially exceeded the original goals including designing, constructing and testing of a scaled-up triple-helix turbine, as well as developing recommendations for application of the turbine for direct water pumping in irrigation systems and for future use in wind farms.

Measurements collected during two years of turbine testing are kept in the PI files.

Table of Contents

1. Abstract.....	1
2. Power of Ocean Streams and Other Ultra Low-Head Hydro Sources.....	2
3. Helical Turbine	5
4. Ocean Power Farm	17
5. Mini Power Stations	31
6. Applications for Ocean Waves	31
7. Helical Turbines for Water Pumping.....	35
8. Wind Farms with Helical Turbines	35
9. A Model for Design and Optimization of the Helical Turbine	41
10. Comparative Performance of Helical vs Darrieus Turbines	47
References.....	53

HELICAL TURBINES AS A NEW TECHNOLOGY FOR HYDRO AND WIND ENERGY IN 21st CENTURY

1. Abstract

This chapter describes the helical turbine as an efficient new instrument for conversion kinetic energy of the hydro streams into electric or other mechanical energy. A multi-megawatt conceptual project of the ocean stream power farm equipped by number of helical turbines is considered along with a concept of a floating factory for insitu production of the hydrogen fuel by means of electrolysis of ocean waters. Besides mega hydro power farms, mini power stations with helical turbines of a few kilowatts each are discussed for small communities or even individual households located near tidal shorelines or river banks with strong water currents. No construction of hydro dams is necessary for such an application. As well as in hydro power plants, compact helical turbines can be used in Wind Farms instead of conventional propeller-type machines of huge diameter. Advantages of such a design for future wind power systems are described below.

A. HYDRO.

Power Farm in the Gulf Stream

Power Farms in Tidal Currents

River Power Stations with no dams

Moored Power Platforms

THE HELICAL TURBINE
IN VARIOUS ENERGY
APPLICATIONS

Helical Turbine-Water Pump

Generators for undersea
unmanned robots

B. WIND.

vertical assembly

horizontal assembly

2. Power of Ocean Streams and Other Ultra Low-Head Hydro Sources.

The kinetic energy of ocean streams (such as the Gulf Stream or the Kuroshiwo current near Japan) as well as tidal and monsoon streams is tremendous. However, the absence of an efficient, low cost and environmentally friendly hydraulic energy converter suited to free flow water is still the major barrier to the exploitation of this renewable energy source. Another well-known barrier to the development of renewable energy is, unfortunately, the low cost of oil that remains the principal component of world energy production. But, it is time to realize that the reserves of oil are limited and rapidly dwindling. Moreover, since hydrocarbons such as oil and coal are of considerable importance as raw materials for industry, especially for future generations, their burning should be limited. And the concept that "life is hard but it's fortunately short" will not help too much here.

For decades scientists and engineers have tried unsuccessfully to utilize conventional turbines for low-head hydro. The very efficient hydraulic turbines in high heads become so expensive in applications for low and ultra low-head hydro electric stations that only a very modest development of this kind can be found in practice. Three principal types of hydraulic turbines are presently used for harnessing hydropower, namely: Kaplan, Francis and Pelton and some of their modifications such as Bulb or Straflo turbines. However, as can be seen from Figure 1, the cost of the Kaplan turbine, one of the most advanced hydraulic turbines, skyrockets when it is used for two meters or lower water heads. For example, the unit cost of the turbine jumps up to about 4 times when the water head falls from 5 to 2 meters.

Fig. 1 Unit Cost of Kaplan Turbine vs Hydraulic Head (by British Manufacturers)

The principal difference between exploitation of high and low head turbines is that the latter has to have a large flow opening to pass huge water masses with low velocities and pressure while conventional turbines are designed for high pressure and relatively small water ducts. So, to use high-pressure turbines for free flow or low-head hydro is the same as using a racing car instead of a tractor for picking up crops although they can both develop the same power.

The energy of fluid flow is described by Bernoulli's equation:

$$z + \frac{p}{\rho} + \frac{V^2}{2g} = \text{const}$$

where component (p/ρ) reflects the energy part that is caused by external pressure (water head), $V^2/2g$ is kinetic energy component and z is the fluid elevation with respect to the reference axis. When z is taken as an origin of coordinates $z = 0$.

Conventional turbines (except Pelton turbine) are designed to utilize mostly the second component of Bernoulli's equation at the expense of the third (kinetic) one. To do so they have to have a so-called "high solidity" where turbine blades cover most of the inside flow passage resisting fluid flow and building up of the water head. In this case the fluid velocity V falls and the component $V^2/2g$ becomes negligibly small compared to the p/ρ component. That is the reason why the higher water head corresponds to the higher efficiency of the hydraulic turbines, reaching magnitudes close to 90% in some cases.

However, the situation is completely reversed for low, ultra-low or free fluid flows. In these

cases the pressure energy component p/ρ is almost vanished and kinetic energy becomes the dominant factor. How would conventional turbines perform in these conditions? They still can demonstrate a relatively good efficiency because of well advanced hydropower technology. But good turbine efficiency using conventional turbines in low head application is achieved at the expense of cost of power as one can see from Figure 1.

In 1931 Darrieus patented his new reaction turbine that, in contrast to the commonly used wheel-type turbines, has a barreled shape with a number of straight or curved-in-plane airfoil blades and a shaft that is perpendicular to the fluid flow. The Darrieus turbine was enthusiastically met by engineers and scientists in both wind and hydro power industries because of its simplicity and because the turbine allowed high speed to develop in slow fluids, maintaining a large passage area without substantially increasing its diameter [1,2]. However, in spite of numerous intensive attempts for decades to utilize the Darrieus rotor, it has not received wide practical applications mostly due to the pulsating nature of its rotation and its relatively low efficiency. Fatigue failure of blades is common in this turbine because of its inherent vibration. It also has a problem of self-starting at low rotational speed due to its straight blades which change angles of attack traveling along a circular path.

3. Helical Turbine

The new Helical Turbine [Fig.2] which was developed in 1994-1995 has all the advantages of the Darrieus turbine without its disadvantages, i.e., allowing a large mass of slow water to flow through, capturing its $V^2/2g$ kinetic energy and utilizing a very simple rotor as a major factor of the

Fig.2. Helical Turbine with electric generator in water-sealed chamber

turbine low cost. The helical arrangement of the rotor blades dramatically changes the performance of the Darrieus-type turbine resulting in the following characteristics:

- a. High speed uniform spinning in relatively slow fluid flow (low pressure fluids),
- b. Unidirectional rotation in reversible fluid currents,
- c. High efficiency,
- d. No fluctuation in torque,
- e. No visible signs of cavitation in water for high rotating speed,
- f. Self-starting in slow waters or winds.

More than 180 measurements made during 1994-1995 testing of 20 small 3.5 in (9cm) dia helical turbine models demonstrated up to 95% greater power and about 50% higher speed than the comparable Darrieus rotor. Based on these experiments we could expect that a scaled up helical turbine would have good efficiency without oscillation in both straight and reverse low-head water flows. A scaled up demonstration project with triple-helix turbine shown in Fig. 3 has validated our expectations.

Three blade helical turbine features a 20-inch diameter. The fiberglass turbine with steel shaft weighs 50 pounds.

Fig.3. Turbine tested in the Cape Cod Canal

The turbine was thoroughly tested during June-August 1996 in the Cape Cod Canal in Massachusetts. The canal itself presents a unique set of parameters attractive for the installation of a tidal energy demonstration project. The tidal current there reverses four times a day and is very turbulent with treacherous eddies, vortices and floating seaweed that somewhat complicates testing of the turbines. The maximum water speed measured at the site was about 5.5 f/s. Turbines developed a firm unidirectional rotation when water velocity was about 1.6-1.8 f/s (about one knot).

The overall view of the test site and power assembly is shown in Figures 4 and 5.

The 3-blade turbine was mounted underneath a small raft (10x8x2 ft) and reinforced by steel braces. The 1.25 inch dia shaft of the turbine was extended upwards through the raft providing data on the turbine's torque and its speed. Turbine dimensions are: Diameter - 24 in.; Height (Length) - 34 in.; Blades profile - NACA-0020 with 7 in. chord.

In spite of the natural difficulties encountered, the turbine demonstrated quite good performance with power coefficient about 35% for maximum loading and water velocities about 5 f/s. Turbine rotational speed under load was about 100 RPM. Velocities higher than 5 f/s were rarely observed at the site. Concerning the seaweed factor, we note that although the high speed of turbine rotation protected it from accumulation of seaweed, a substantial amount of the grass did build up on elements of the supporting frame. We also observed a substantial corrosion of aluminum parts of the frame at their contacts with steel parts due to electrolysis in salt water. All of these factors should be taken into account for the future design.

The following specific characteristics of the turbine make it different from other hydraulic machines. The turbine consists of one or more long helical blades that run along an imaginary cylindrical surface of rotation like a screw thread (Fig. 6). The helical airfoil blades provide a

VERTICAL LIFT RR BRIDGE

Length of Center Span: 554 feet
 Vertical Vessel Clearance: 136 feet
 (in raised position)

CAPE COD CANAL

Total Length: 17.4 miles
 Land Cut Length: 7.8 miles
 Approach Channels Length: 9.6 miles
 Controlling Depth: 32 feet
 Bottom Width: 480 feet

SCALE IN YARDS
 500 0 500 1000

Fig.4. Test site in the Cape Cod Canal

Fig.5. Raft/Turbine assembly ready for testing
Cape Cod Canal, Aug. 1996

The helical turbine consists of long blades running along a cylindrical surface like a screw thread. The blades can provide a reaction thrust from flows in either direction without significant vibration. The design of the turbine allows the engineer to reduce the relative diameter (D) of the machine while simultaneously increasing its length (L) with no power losses, providing important benefits in hydro project design.

Fig.6. Double-helix rotor

reaction thrust perpendicular to the leading edges of the blades that can pull them faster than the fluid flow itself. The high speed without any vibration of the helical turbine in a relatively slow fluid, along with structural simplicity, is the key to its good efficiency. A more detailed technical description of the turbine is provided in references [3,4,5].

The helical turbine allows reduction of its diameter while simultaneously increasing its length with no power losses. This is an interesting and advantageous feature of the turbine that can affect the traditional approach to design of a power house, as is shown below.

Any high speed hydraulic or gas turbine has a strength limit that corresponds to the maximum power output. Since the linear velocity reaches its maximum on the periphery of a rotating wheel, it is clear that the major portion of the torque is developed by the parts of the turbine farthest from its center of rotation. This is one of the reasons why engineers try to design turbines of maximum diameter with numerous short blades positioned along the outside boundary of the wheel. The bigger the turbine diameter, the greater its power output for the same angular speed ω and the same shape and sizes of the blades.

However, there are limits to how much the diameter of the turbine can be increased due to the possibility of structural failure caused by centrifugal forces and other dynamical effects.

From this point of view, the helical turbine has a unique advantage since its length L is not limited by centrifugal forces and can be as long as desired. The product DL is approximately equal to the cross-sectional area of the fluid flowing through the helical turbine.

It is apparent from this discussion that the helical turbine allows a new approach to the design of hydraulic or gas power systems using prefabricated turbine modules. Indeed, if a helical turbine module is designed for optimal airfoil and for optimal ω , D and L , the entire power system can be

assembled from such modules in either way, shown in Fig. 7. It will be simpler to construct and exploit a power station, using multiple helical module turbines because a common shaft can be used for a number of turbines and a single electric generator. We have to note, that the shaft will not be needed in most applications where turbines can be bolted to each other. In this case the torque from each turbine will be transmitted directly to the adjacent turbine by connectors on side discs. The modular design of the turbine runner will simplify the maintenance of the station and reduce cost of its construction.

In November 1997 the scaled-up triple-helix turbine shown in Fig. 8 was thoroughly tested at the University of Michigan Hydrodynamics Laboratory by the Allied Signal Aerospace Company, which also supports the research project. The turbine was mounted vertically underneath a rolling bridge and then pulled with different speeds through the fresh water of the 360-foot long canal. The range of velocities during the test was from one to ten ft/sec. No shrouding or ducting was used to improve inflow or outflow of the water through the turbine. The objective of the test was to observe performance of the free helical rotor in the natural water streams.

Three basic characteristics were measured and documented during the test: relative velocity V of the current, ft/s (i.e. the speed of the rolling bridge); torque T developed by the turbine shaft, lb-in; and angular velocity ω of the turbine, rpm. Then turbine power P_t is calculated as $P_t = T \omega$, and turbine efficiency (power coefficient) is calculated as $\eta = P_t / P_w$, where $P_w = 0.5 \rho A V^3$ is the power of the water flow that corresponds to the cross-sectional area A of the turbine. In this case $A = 40 \times 33 \text{ in}^2$. Torques T were registered by the torquemeter attached to the turbine shaft. The torquemeter was equipped with a hydraulic brake device, which allowed for changing the loading on the turbine. During each run with fixed water velocity V , the torque T gradually increased until

Fig.7. Various Turbine Assemblies

The flexibility and adaptability of the helical turbine could allow multiple units to be configured in sequence at a small hydropower site. As shown in this figure, the turbines could use common shafts and a single electric generator. In ultra low-head applications, the shaft-connected rotors could operate free in the water. Where head or other flow conditions required, simple casings could be designed. The modular design of the turbine runner would simplify the maintenance.

Fig.8. Triple-helix turbine 40(dia)x33in tested in University of Michigan

the maximum magnitude $T_{\max}$ which the turbine can carry without stopping. This instant corresponds also to the point of maximum turbine power $P_{\max}$ at minimum angular velocity ω .

Figures 9 and 10 demonstrate major results of the test. The data shown are calculated for maximum turbine power at each magnitude of the water velocity V . As one can see from Fig. 5, the turbine develops a very stable efficiency around 35% at all water velocities. Starting with a firm rotation at water flow V about 1 knot, the turbine increases its power in proportion to the water velocity cubed. No oscillation or vibration of the turbine was observed during the test.

Tip ratio V_t/V , where V_t is the linear velocity of the turbine blade, depended on magnitude of the loading torque. For the maximum torque applied to the shaft, the tip ratio was quite stable in the range of 2.0-2.2.

4. Ocean Power Farm

Helical turbines can be used as the key power modules in the design of ocean power farms for harvesting the energy of ocean streams. Such farms, if built in major ocean streams such as the Gulf Stream near the North American continent or the Kuroshiwo Current near Japan, can produce hundreds or even thousands of megawatts of electric power. Moreover, once installed in the ocean stream, the power farm can be expanded in the future as much as desired since the energy potential of the ocean streams is greater than any imaginable requirements of mankind. For example, the mass of water carried by the Gulf Stream in the Atlantic Ocean at 38° North Latitude is 82 million m^3/s , which is many times greater than the water flow of all the Earth's rivers together.

Turbine Performance
University of Michigan Tests

Fig.9. Output Power VS Water Flow

Turbine Performance University of Michigan Tests

Fig.10. Turbine Efficiency

The following is a conceptual approach to the design of a straight or reversible (tidal) ocean stream power farm using helical turbines to extract energy from the water current. Turbines will be positioned vertically. This makes power production of the entire farm independent of the direction of the water stream since the helical turbines are unidirectional rotation machines. Such a design is especially advantageous in reversible tidal streams or streams that change direction depending on which way the winds blow, for example, during monsoons.

We consider the three-blade helical turbine shown in Fig. 8 as the optimal power module for this project. As mentioned, this turbine has demonstrated 35% efficiency in free water flow.

Since overall dimensions of a stream farm, namely its length, width and depth depend on the designed power capacity, it is convenient to choose a reasonably small modular farm and then to increase the project capacity if necessary by adding more modules. Such a floating modular farm schematic, shown in Figures 11 and 12, consists of the following principal mechanical and structural components:

- a. Helical Turbines;
- b. Electric generators, each of them designed to pick up power from a vertical assembly of 16 turbines mounted one upon another;
- c. A floating frame constructed from prefabricated longitudinal, lateral and vertical elements, which could be built from metallic or plastic tubings. The frame performs two functions:
 1. As a structural system, which provides the integrity and strength of the farm, and

Fig.11. Stream Farm Schematic

Fig.12. Detail of the Farm

2. As a pontoon, which maintains flotation of the farm at the designated depth level;
- d. Anchors that secure the position of the farm against the ocean current pressure and the hydrostatic lifting force.

Figure 11a presents the top view of the farm with dimensions of 40 x 40 meters between axes of the extreme turbine rows. The side elevation is shown in Fig. 11b. The farm consists of five rows of vertical turbine assemblies, each of 16 modular turbines, mounted on a common shaft with one electric generator on the top. Every other inner row contains four turbine assemblies. The span of 10 meters between adjacent turbines along orthogonal axes is chosen to be big enough to reduce interference of the turbines with each other, and to be reasonably small enough to avoid unjustifiable expansion of the structure. To minimize obstruction of the turbines against water flow through the farm, it must be turned horizontally to make a small angle α with respect to the ocean stream (see Figures 11 and 13). In this case all the turbines would fully open to the water pressure from the stream. The smallest offset angle is $\alpha = 6^\circ$ in our case, as in the diagram of Fig. 13. Also, to protect the farm against the damaging effect of storm waves the entire structure can be positioned 10-15 meters or even deeper below the ocean surface.

To estimate the overall power capacity and cost of the modular stream farm, let us consider the specific conditions of the Gulf Stream where the water velocity is $V=2.5$ m/s, i.e. a little less than

Fig.13. Angular Offset of Farm Position

5 knots. Taking the cross-section frontal area of the turbine $A=0.865\text{m}^2$ we calculate power of the

free water flow through such a section as

$$P_w = 1/2 \rho A V^3 = 6.87 \text{ kW}$$

where density ρ of the sea water is about 1015 kg/m^3 .

The power of one turbine with its 35% efficiency is calculated as

$$P_t = 0.35 P_w = 2.4 \text{ kW}.$$

Because the modular farm contains $16 \times 41 = 656$ turbines the total power of the module P_m is

$$P_m = 1.6 \text{ MW}.$$

Taking into account the combined efficiency of electric generators (including losses in electric circuits) as 85% we can obtain the modular farm power output

$$P_m = 1.36 \text{ MW} = 1,360 \text{ kW}.$$

Approximate cost estimation for elements of the farm includes:

1.	One turbine as shown in Fig. 3	\$ 700
2.	38 kW power waterproofed electric generator for assembly of 16 turbines	\$ 2,000
3.	40x40x12m frame from prefabricated tubings with some steps and small platforms	\$1,000,000
4.	Anchors	\$ 300,000
5.	Electric cables, connectors etc.	\$ 100,000
6.	Other mechanical and electrical supplies	\$ 100,000
7.	Transportation, installation under the water and leveling of the farm	\$1,000,000

Thus, the total cost of the modular farm would be

$$C = \$700 \times 656 + \$2,000 \times 41 + \$1,000,000 + \$300,000 + \$1,000,000 + \$100,000 + \$1,000,000 = \$3,040,000$$

This converts into the unit cost of the installed power

$$C_u = \$3,040,000 / 1,360 \text{ kW} = \$2,235/\text{kW}.$$

The cost of operation of the farm was not included in the above analysis. This cost would depend on the specific requirements for the technological operation of the farm in other words where and how the electric power generated would be used, etc.

For comparison, the unit costs for the construction of other well-developed power technologies are summarized in the following table:

Unit cost of installed power in \$/kW		
	Technology	Cost
1.	Nuclear	2,500
2.	Coal Fired	1,500
3.	Oil Steam Plant	1,300
4.	Conventional Hydro (site dependent)	1,500-2,500
5.	Solar	5,000-8,000

Thus our calculation of \$2,235/kW for an ocean power farm is compatible with prices of other power technologies.

However, the helical turbines do not need any fuel for their operation and do not pollute the water or air. From this point of view the ocean power farm can be compared with solar power systems, which are substantially more expensive.

We believe that a reasonable field size for a power farm under Gulf Stream conditions should be 400x400m containing 100 modular farm units as discussed. Such a stream farm would generate continuously about 140 megawatts, and its construction cost would be around C=300 million dollars. A pictorial view of such a farm is shown in Figure 14.

The final issue to be addressed is how and where to use the electric power generated by the ocean stream farms. We envision two obvious options. The first one is to transmit electric power

Fig.14. Projected Ocean Power Farm

cable on the ocean floor when such a project becomes technically and economically feasible.

The second option is to utilize the farm power insitu for year-round production of hydrogen fuel by electrolysis of the ocean waters. Liquefied or stored by any other method, hydrogen can then be transported everywhere to be used either instead of gasoline in internal combustion engines or in fuel-cell motors. We studied such an option in our earlier projects and found it feasible if cheap electric power is available in large quantities [6]. For insitu production of hydrogen fuel a well equipped floating electro-chemical factory should be positioned next to the stream farm. This factory would use electric power from the farm to resolve the ocean water into hydrogen, oxygen and some other chemical by-products and store them for further transportation. Obsolete tankers or other large naval vessels can be converted into such factories. Figure 13 illustrates the ocean power project described, including both the stream farm and the floating hydrogen production factory on the open ocean.

As mentioned, the power capacity of the stream farm can easily be increased by adding more helical turbine modules. One can visualize mega-power farms such as those illustrated in Figure 14, in the Gulf Stream or the Kuroshiwo current able in the near future to generate thousands of megawatts of electric power. Such ocean power farms with helical turbines can be of particular value for future floating cities, which have been projected for overpopulated countries such as Japan. Fig. 15 demonstrates the possibility of using the power farm as a permanent power supply source for such a floating city.

Fig.15.

Helical Turbines as a Power Source for Marine Cities

A floating farm of 0.16
km² area with Helical
turbines can harness up
to 140 Megawatts from
oceanic currents such as
the Gulf Stream or the
Kuroshiwo current .

5. Mini Power Stations

The new helical turbine technology opens up prospects for design of mega-projects to harness the limitless energy of ocean streams and tides.

However, there are thousands of sea and river sites in the world where small power stations can be constructed to supply electric power to local consumers. Such mini power stations of 2-5 kilowatts can be easily built and utilized by small communities or even individual households located near direct or reversible water streams. Assembly of a few helical turbines such as shown in Fig. 16 can supply a small consumer with permanent electric power from the renewable hydro energy source, without construction of any dam.

In this case the global macro energy objective would be solved by means of using a numerous mini power installations, discussed.

6. Applications for Ocean Waves.

The kinetic energy of ocean waves also is an untapped, renewable energy source. The absence of reliable and low cost technologies to convert this energy to useable electrical energy is the major barrier to exploitation of this abundant energy source. However, the helical turbine offers a solution to this difficult problem either. Fig. 17 demonstrates one of the possible applications of helical turbines in this case.

Power output from the helical turbine is proportional to the flow rate cubed. While open ocean currents in many locations are below the power threshold of the turbine, wave-generated flows are typically in the range of 2-10ft/sec with direction reversals every 5-12 seconds. Flows of this magnitude are capable of producing significant power with even relatively small turbines.

A PROJECT OF AN INDEPENDANT POWER STATION WITH TWO HELICAL TURBINES IN OCEAN OR RIVER CURRENTS

Unit helical turbine

Power output (minimal):

<u>water velocity</u>	<u>kilowatts</u>
2 m/s	2.4 kw
3 m/s	8.1 kw

Fig.16. Mini Power Stations

Fig.17. Helical Turbine as an continuous Energy Source in Water Currents

Deep water surface moorings used for oceanographic research typically use 10' diameter discus or hemispherical buoys with 8-20,000 lbs. of buoyancy. They are moored with a combination of wire rope and nylon line. The nylon provides compliance for waves, current and winds. As the surface buoy moves with the seas, the motion is converted to primarily vertical oscillations on the mooring line. In the wire section of the mooring, the flow rates produced are in the 2-10 ft/sec range depending on wave height and period. A helical turbine with its rotational axis perpendicular to the mooring line will rectify the oscillatory flow of the line and produce power proportional to the cube of the instantaneous velocity. Multiple turbines can be deployed on a mooring to provide power to various sensors, sound projectors, or other energy intensive instruments.

Surface moorings are not the only means of extracting wave power with the helical turbine. A subsurface mooring with the buoyancy element positioned near the surface experiences substantial forcing at wave frequencies due to fluctuating pressure and drag at the subsurface buoy. With a long steel or nylon mooring line, these forces cause the mooring to oscillate along the vertical axes at its natural period. The amplitude of the oscillation is a function of the compliance of the mooring material and the frequency of oscillation is a function of the mooring design. A properly tuned mooring can be made to oscillate substantially at typical wave periods and thereby provide significant vertical velocities that can be harnessed by the turbine.

Finally, in shallow water a vertical mounted turbine near the bottom would be exposed to substantial horizontal oscillary flows generated by waves at the surface. Depending on the water depth and the wave period, these horizontal flows may be as large as the vertical flows seen on deep water moorings. Thus, we can identify three potential wave power generating systems, namely, surface moorings, subsurface moorings, and bottom moorings (shallow water only).

7. Helical Turbines for Water Pumping.

A substantial portion of the electric power in many developing countries is used to pump water from rivers into irrigation supply systems. This is a common situation in such countries as India, Pakistan, and Egypt where there is intensive use of irrigation canals in agricultural technology. The helical turbine can be very helpful in these cases because it can directly convert kinetic energy of river water flow into mechanical energy to operate water pumps.

Figure 18 demonstrates components of the "helical turbine-water pump" assembly designed to supply water from the river directly into an irrigation system. No intermediate generating of electric power is needed in such an installation. One or more turbines can be mounted in the chain depending on turbine capacities, water pumping rate and water velocity in the river. Assembling more turbines on the same shaft across the water flow would increase overall power of the pump station accordingly to the water demands.

The "helical turbine-pump" system, once installed in the river, becomes, in certain respects, a "perpetual motion" (excluding maintenance) device supplying water as long as the river keeps flowing. This system should find wide application in developing countries due to its obvious simplicity and low cost.

8. Wind Farms with Helical Turbines.

The hydraulic helical turbine is recognized by hydro power corporations and individuals around the world as an efficient new apparatus to harness hydro energy from ocean streams, tidal estuaries, low head rivers and canals. The turbine performance has been proven in both laboratory and field testing. The performance characteristics of the turbine, which include independence of

Top View

Fig.18. "HELICAL TURBINE-WATER PUMP" SYSTEM FOR IRRIGATION

the direction of the fluid flow, pulsation-free rotation over the entire cycle, and high efficiency, make the helical turbine an excellent candidate for application in wind power systems, too. This turbine should demonstrate about the same characteristics in wind harnessing installations as it does in water. However, its design for wind requires a different approach for optimization due to different air density, viscosity, exploitation conditions and velocity of rotation.

We suggest a Wind Farms design using multiple standard-sized helical turbines in two different options as follows:

- a. Horizontal assembly of the turbines (Fig. 19)
- b. Vertical assembly of the turbines (Fig. 20)

Design "a" is more power efficient than design "b" because all the turbines are elevated high above the ground where winds are usually much stronger than near the land surface. The disadvantage of such a system is its dependence on the direction of the wind blow, in other words, from the angle between the direction of wind and the axis of turbine rotation. For design "a" the maximum power would be generated if wind flow is perpendicular to the turbine shafts. If the wind can change its direction with respect to the turbine axis, design "b" should be used.

Compared with a conventional wind power system using a high tower with single big diameter propeller, the helical turbine has the following advantages for wind applications:

- It rotates in the same direction even if the wind changes its directions,
- It does not pulsate in constant wind velocity in contrast to the Darrieus wind rotor,
- Maintenance of the wind farm is simple because any turbine in the system can be easily removed and replaced,

- The same size relatively small standard helical turbines can be used for wind farms of different power capacities.

Fig.19. Wind Farm with horizontal helical turbines

Fig.20. Wind Farm with vertical helical turbines

9. Mathematical Model for Design and Optimization of the Helical Hydraulic Turbine.

Let us consider a stationary turbine with a helical blade that runs along the thread line AME on the surface of a cylinder of height L and radius R (Fig. 21). Equation of the helix is defined by

$$x = R \cos \varphi, \quad y = R \sin \varphi, \quad z = R \varphi \tan \delta \quad (1)$$

where x , y and z are coordinates of the point M of the helix, and δ is the angle of inclination of the blade to the XOY plane.

We assume, as an approximation, that the cross-section of the blade has the shape of an infinitely thin rectangle with its length equal to the chord b of the blade's airfoil. This does not change the proportion between lifts and drags after resolution of the reaction force F which can be calculated as

$$F = k_0 A V_w^2 \quad (2)$$

where: k_0 - constant. In this case k_0 is set to about 1.2 ρ (ρ - water density),

A - projection of the frontal area of the blade on the plane perpendicular to the water flow,

V_w - water velocity.

Designating a segment of the curve AME by ξ we obtain

$$d\xi = R(1 + q^2)^{1/2} d\varphi = \frac{R}{\cos \delta} d\varphi, \quad \text{where } q = \tan \delta \quad (3)$$

From (3):

$$\begin{aligned}\xi &= R(1 + q^2)^{1/2} \varphi = \frac{R}{\cos \delta} \varphi, \\ \varphi &= \frac{\cos \delta}{R} \xi = \frac{\xi}{R\sqrt{1+q^2}}.\end{aligned}\tag{4}$$

On the other hand

$$\begin{aligned}z^2 + (R\varphi)^2 &= \xi^2 \\ L^2 + (R\varphi_0)^2 &= l^2\end{aligned}$$

where:

l is the length of the blade,

$\varphi_0 = \varphi_{\max}$ is the angle of twist of the entire blade.

Let's designate the angle of attack by α . Then, at any point M

$$\sin \alpha = \cos \varphi \text{ and } \cos \alpha = \sin \varphi.\tag{5}$$

The torque T is obtained from the equation

$$T = FR \cos \alpha\tag{6}$$

Substituting (2) in (6) we obtain torque ΔT for a small area of the blade $\Delta A = b\Delta \xi \sin \alpha$:

$$\Delta T = k_0 b \Delta \xi V_w^2 R \sin \alpha \cos \alpha\tag{7}$$

where b is the airfoil cord, and $\Delta \xi$ is a small segment of the blade along the AME line.

When $\Delta \xi \rightarrow 0$

$$T = k_1 \int_0^1 \sin \alpha \cos \alpha \, d\xi \quad (8)$$

where

$$k_1 = k_0 \, b \, V_w^2 \, R \quad (9)$$

From (4), (5) and (8)

$$T = k_1 R \sqrt{1+q^2} \int_0^{\varphi_0} \cos \varphi \sin \varphi \, d\varphi = k_1 R \frac{\sqrt{1+q^2}}{2} \sin^2 \varphi_0 \quad (10)$$

Since $q = \tan \delta = \frac{L}{\varphi_0 R}$, the total starting torque developed by the blade in the water flow V_w can be expressed as

$$T = k_2 \sqrt{1+q^2} \sin^2 \left(\frac{L}{Rq} \right) \quad (12)$$

where

$$k_2 = \frac{1}{2} k_1 R \quad (13)$$

Or, in dimensionless representation:

$$T_1 = \frac{T(q)}{k_2} = \sqrt{1+q^2} \sin^2 \left(\frac{L}{Rq} \right) \quad (14)$$

Figure 22 represents the torque T_1 as a function of angle of blade inclination δ and the ratio L/R of the turbine height to its radius. It is remarkable that the torques reach their maximums for different δ with changing L/R . The angle δ increases with increasing ratio L/R . It means that for the constant R the higher turbine has to have its helical blades closer to the vertical line in order to obtain the maximum torque.

Fig.21. Development of the blade line on vertical plane

3D Diagram $T_1 = f(L/R, \delta^\circ)$

2D Diagram for $L/R = 2$

2D Diagram for $L/R = 3$

Fig.22. Torque as a function of angle δ and L/R ratios

10. Comparative Performance of Helical vs Darrieus Turbines.

Since the helical turbine is a modification of the well known Darrieus rotor, it was possible to compare them in almost identical laboratory tests.

The following same size turbines were thoroughly tested and compared:

- Helical Turbine with 3 blades twisted on 60° angle,
- Darrieus Turbine with 3 straight blades.

Heights of both turbines are 9 in., diameter 8.5 in. The airfoil cross-sections are NACA-0020. Plastic blades were built at the SLA-190 rapid prototyping machine. Two plastic disks are used on both sides of each turbine for mounting blades and transmitting torques. The objective of the experiment was to compare two turbines but not to optimize them to obtain the maximum efficiency.

Each turbine was tested in the water flow with small heads ranging from 1 to 8.5 inches and water velocities from 0.9 to 2.4 ft/s.

The following tables summarize the collected data for the turbines.

A. Helical Turbine

Water Head [in]	Water Power [watts]	Peak Turbine Power [watts]	Peak Efficiency [%]
1.0	3.1	0.5	16.2
2.25	10.5	1.95	18.6
3.0	16.6	3.21	19.3
4.75	30.0	5.85	19.5
6.5	54.8	11.9	21.7

B. Darrieus Turbine

Water Head	Water Power	Peak Turbine Power	Peak Efficiency
[in]	[watts]	[watts]	[%]
2.0	7.9	0.8	10.5
3.25	16.1	2.0	12.4
5.0	29.2	4.2	14.3
7.75	57.2	9.7	16.9
8.5	65.1	12	18.4

Diagrams of Figures 23 and 24 as well as tables A and B reflect comparative characteristics of both turbines including turbines' power and their efficiency (power coefficients) depending on water heads and water power. As can be seen from these charts the helical turbine demonstrates substantially better performance than the Darrieus rotor in all major characteristics including turbine power, efficiency and speed of rotation. In many comparisons the helical turbine is in excess of 50% and higher.

Experiments revealed the remarkable advantage of the helical turbine over the Darrieus rotor, namely, its smaller resistance to the water flow. This resistance depends on the turbine's so called solidity defined as

$$\sigma = \frac{bi}{D}$$

where "b" is chord of the blade section, "i" is number of blades and "D" is turbine diameter. The larger the product "bi", the greater is the resistance of the turbine to the water flow for the same D.

However, this resistance depends also on the turbine's speed of rotation. The higher the turbine speed, the more it obstructs the stream. A very fast rotating turbine in free water with no ducting would practically stop the water flow through it, reducing turbine efficiency to zero.

Thus, turbine resistance is a very important characteristic that can substantially reduce efficiency of turbines in free currents. Most of the water simply avoids the turbine without producing any useful work, when the turbine develops high resistance to the water flow. In our experiments the turbine resistance was evaluated by measuring elevation of the water level (water heads) in front of the rotating turbine. Those observation are reflected in charts of Figure 25 showing both helical and Darrieus turbines.

As one can see, the Darrieus turbine develops water heads from 30% to 50% higher than the helical turbine in all ranges of their rotating velocities (rpm). For example, the ratio of water heads of Darrieus and Helical turbines for 150 RPM turbine speed without load is about 1.5 (top chart of Fig. 25). This ratio remains the same (1.5) for turbines under maximum load and the same velocity 150 RPM (bottom chart of Fig. 25). So, in both cases the Darrieus turbine exhibited 50% stronger resistance to the water flow than the same size helical turbine.

Another important characteristic of hydraulic turbines which actually triggered the present research is their oscillation and vibration under the load. Oscillation of the turbine causes not only fluctuation of the electric power, but it also leads to the fast failure of mechanical parts and joints in the "turbine-generator-transmission" chain. From this point of view, the helical turbine demonstrates obvious superiority to the Darrieus-type rotor. While the helical turbine did not show

any sign of vibration during testing, the Darrieus turbine oscillated substantially in all the experiments. Pulses from the Darrieus turbine were especially strong when its blades passed the walls of the water channel.

Fig.23. Peak Turbine Power Versus Water Head

Fig.24. Peak Turbine Efficiency Versus Water Head

Fig.25. Turbine rotation with and without loading

REFERENCES

1. T.D. Faure, B.D. Pratte, D. Swan; The Darrieus Hydraulic Turbine-Model and Field Experiments, Proc. 4th Int'l Symposium on Hydropower Fluid Machinery, ASME, New York, 1986.
2. Y. Takamatsu, A. Furukawa, K. Okuma, K. Takenouchi; Experimental Studies on a Preferable Blade Profile of Darrieus-type Cross-flow Water Turbine. JSME International Journal, Vol. 34, No. 2, 1991.
3. Gorlov, A.M. The Helical Turbine: A New Idea for Low-Head Hydro. Hydro Review, No. 5, 1995.
4. Gorlov, A.M., Unidirectional Helical Reaction Turbine, U.S. Patent No. 5,451,137, Sep. 19, 1995.
5. Gorlov, A.M. and Rogers, K. Helical Turbine as Undersea Power Source, Sea Technology, Dec. 1997.
6. Gorlov, A.M., Hydrogen as an Activating Fuel for Tidal Power Plant. Int'l Journal of Hydrogen Energy, Vol. 6, No. 3, 1981.