and Near-surface Turbulence. Heat and Momentum Fluxes at the Sea Surface. Heat Transport and Climate. Indian Ocean Equatorial Currents. Internal Waves. Island Wakes. Langmuir Circulation and Instability. Mesoscale Eddies. Open Ocean Convection. Pacific Ocean Equatorial Currents. Turbulence in the Benthic Boundary Layer. Upper Ocean Mixing Processes. Vortical Modes.

Further Reading

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TIDAL ENERGY

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Introduction

Gravitational forces between the moon, the sun and the earth cause the rhythmic rising and lowering of ocean waters around the world that results in Tide Waves. The moon exerts more than twice as great a force on the tides as the sun due to its much closer position to the earth. As a result, the tide closely follows the moon during its rotation around the earth, creating diurnal tide and ebb cycles at any particular ocean surface. The amplitude or height of the tide wave is very small in the open ocean where it measures several centimeters in the center of the wave distributed over hundreds of kilometers. However, the tide can increase dramatically when it reaches continental shelves, bringing huge masses of water into narrow bays and river estuaries along a coastline. For instance, the tides in the Bay of Fundy in Canada are the greatest in the world, with amplitude between 16 and 17 meters near shore. High tides close to these figures can be observed at many other sites worldwide, such as the Bristol Channel in England, the Kimberly coast of Australia, and the Okhotsk Sea of Russia. **Table 1** contains ranges of amplitude for some locations with large tides.

On most coasts tidal fluctuation consists of two floods and two ebbs, with a semidiurnal period of about 12 hours and 25 minutes. However, there are some coasts where tides are twice as long (diurnal tides) or are mixed, with a diurnal inequality, but are still diurnal or semidiurnal in period. The magnitude of tides changes during each lunar month. The highest tides, called spring tides, occur when the moon, earth and sun are positioned close to

a straight line (moon syzygy). The lowest tides, called neap tides, occur when the earth, moon and sun are at right angles to each other (moon quadrature). Isaac Newton formulated the phenomenon first as follows: 'The ocean must flow twice and ebb twice, each day, and the highest water occurs at the third hour after the approach of the luminaries to the meridian of the place'. The first tide tables with accurate prediction of tidal amplitudes were published by the British Admiralty in 1833. However, information about tide fluctuations was available long before that time from a fourteenth century British atlas, for example.

Rising and receding tides along a shoreline area can be explained in the following way. A low height tide wave of hundreds of kilometers in diameter runs on the ocean surface under the moon, following its rotation around the earth, until the wave hits a continental shore. The water mass moved by the moon's gravitational pull fills narrow bays and river estuaries where it has no way to escape and spread over the ocean. This leads to interference of waves and accumulation of water inside these bays and estuaries, resulting in dramatic rises of the water level (tide cycle). The tide starts receding as the moon continues its travel further over the land, away from the ocean, reducing its gravitational influence on the ocean waters (ebb cycle).

Table 1 Highest tides (tide ranges) of the global ocean

Country	Site	Tide range (m)
Canada	Bay of Fundy	16.2
England	Severn Estuary	14.5
France	Port of Ganville	14.7
France	La Rance	13.5
Argentina	Puerto Rio Gallegos	13.3
Russia	Bay of Mezen (White Sea)	10.0
Russia	Penzhinskaya Guba (Sea of Okhotsk)	13.4

The above explanation is rather schematic since only the moon's gravitation has been taken into account as the major factor influencing tide fluctuations. Other factors, which affect the tide range are the sun's pull, the centrifugal force resulting from the earth's rotation and, in some cases, local resonance of the gulfs, bays or estuaries.

Energy of Tides

The energy of the tide wave contains two components, namely, potential and kinetic. The potential energy is the work done in lifting the mass of water above the ocean surface. This energy can be calculated as:

$$E = \mathbf{g}\rho A \int z \, \mathrm{d}z = 0.5 \mathbf{g}\rho A h^2,$$

where E is the energy, $\mathbf{g}$ is acceleration of gravity, ρ is the seawater density, which equals its mass per unit volume, A is the sea area under consideration, z is a vertical coordinate of the ocean surface and h is the tide amplitude. Taking an average $(\mathbf{g}\rho) = 10.15 \, \mathrm{kN \, m^{-3}}$ for seawater, one can obtain for a tide cycle per square meter of ocean surface:

$$E = 1.4 h^2, \text{watt-hour}$$

or

$$E = 5.04 h^2, \text{kilojoule}$$

The kinetic energy T of the water mass m is its capacity to do work by virtue of its velocity V. It is defined by $T = 0.5 \, m V^2$. The total tide energy equals the sum of its potential and kinetic energy components.

Knowledge of the potential energy of the tide is important for designing conventional tidal power plants using water dams for creating artificial upstream water heads. Such power plants exploit the potential energy of vertical rise and fall of the water. In contrast, the kinetic energy of the tide has to be known in order to design floating or other types of tidal power plants which harness energy from tidal currents or horizontal water flows induced by tides. They do not involve installation of water dams.

Extracting Tidal Energy: Traditional Approach

People used the phenomenon of tides and tidal currents long before the Christian era. The earliest navigators, for example, needed to know periodical tide fluctuations as well as where and when they could use or would be confronted with a strong tidal current. There are remnants of small tidal hydromechanical installations built in the Middle Ages around the world for water pumping, watermills and other applications. Some of these devices were exploited until recent times. For example, large tidal waterwheels were used for pumping sewage in Hamburg, Germany up to the nineteenth century. The city of London used huge tidal wheels, installed under London Bridge in 1580, for 250 years to supply fresh water to the city. However, the serious study and design of industrial-size tidal power plants for exploiting tidal energy only began in the twentieth century with the rapid growth of the electric industry. Electrification of all aspects of modern civilization has led to the development of various converters for transferring natural potential energy sources into electric power. Along with fossil fuel power systems and nuclear reactors, which create huge new environmental pollution problems, clean renewable energy sources have attracted scientists and engineers to exploit these resources for the production of electric power. Tidal energy, in particular, is one of the best available renewable energy sources. In contrast to other clean sources, such as wind, solar, geothermal etc., tidal energy can be predicted for centuries ahead from the point of view of time and magnitude. However, this energy source, like wind and solar energy is distributed over large areas, which presents a difficult problem for collecting it. Besides that, complex conventional tidal power installations, which include massive dams in the open ocean, can hardly compete economically with fossil fuel (thermal) power plants, which use cheap oil or coal, presently available in abundance. These thermal power plants are currently the principal component of world electric energy production. Nevertheless, the reserves of oil and coal are limited and rapidly dwindling. Besides, oil and coal cause enormous atmospheric pollution both from emission of greenhouse gases and from their impurities such as sulfur in the fuel. Nuclear power plants produce accumulating nuclear wastes that degrade very slowly, creating hazardous problems for future generations. Tidal energy is clean and not depleting. These features make it an important energy source for global power production in the near future. To achieve this goal, the tidal energy industry has to develop a new generation of efficient, low cost and environmentally friendly apparatus for power extraction from free or ultra-low head water flow.

Four large-scale tidal power plants currently exist. All of them were constructed after World War II. They are the La Rance Plant (France, 1967), the Kislaya Guba Plant (Russia, 1968), the Annapolis Plant (Canada, 1984), and the Jiangxia Plant

Table 2 Extant large tidal power plants

Country	Site	Installed power (MW)	Basin area (km²)	Mean tide (m)
France	La Rance	240	22	8.55
Russia	Kislaya Guba	0.4	1.1	2.3
Canada	Annapolis	18	15	6.4
China	Jiangxia	3.9	1.4	5.08

(China, 1985). The main characteristics of these tidal power plants are given in **Table 2**. The La Rance plant is shown in **Figure 1**.

All existing tidal power plants use the same design that is accepted for construction of conventional river hydropower stations. The three principal structural and mechanical elements of this design are: a water dam across the flow, which creates an artificial water basin and builds up a water head for operation of hydraulic turbines; a number of turbines coupled with electric generators installed at the lowest point of the dam; and hydraulic gates in the dam to control the water flow in and out of the water basin behind the dam. Sluice locks are also used for navigation when necessary. The turbines convert the potential energy of the water mass accumulated on either side of the dam into electric energy during the tide. The tidal power plant can be

Figure 1 Aerial view of the La Rance Tidal Power Plant (Source: Electricité de France).

designed for operation either by double or single action. Double action means that the turbines work in both water flows, i.e. during the tide when the water flows through the turbines, filling the basin, and then, during the ebb, when the water flows back into the ocean draining the basin. In single-action systems, the turbines work only during the ebb cycle. In this case, the water gates are kept open during the tide, allowing the water to fill the basin. Then the gates close, developing the water head, and turbines start operating in the water flow from the basin back into the ocean during the ebb.

Advantages of the double-action method are that it closely models the natural phenomenon of the tide, has least effect on the environment and, in some cases, has higher power efficiency. However, this method requires more complicated and expensive reversible turbines and electrical equipment. The single action method is simpler, and requires less expensive turbines. The negative aspects of the single action method are its greater potential for harm to the environment by developing a higher water head and causing accumulation of sediments in the basin. Nevertheless, both methods have been used in practice. For example, the La Rance and the Kislaya Guba tidal power plants operate under the double-action scheme, whereas the Annapolis plant uses a single-action method.

One of the principal parameters of a conventional hydropower plant is its power output P (energy per unit time) as a function of the water flow rate Q (volume per time) through the turbines and the water head h (difference between upstream and downstream water levels). Instantaneous power P can be defined by the expression: $P = 9.81\,Qh$, kW, where Q is in $m^3\,s^{-1}$, h is in meters and 9.81 is the product (ρg) for fresh water, which has mass density $\rho = 1000\,kg\,m^{-3}$ and $g = 9.81\,m\,s^{-2}$. The (ρg) component has to be corrected for applications in salt water due to its different density (see above).

The average annual power production of a conventional tidal power plant with dams can be calculated by taking into account some other geophysical and hydraulic factors, such as the effective basin area, tidal fluctuations, etc. **Tables 2** and **3** contain some characteristics of existing tidal power plants as well as prospects for further development of traditional power systems in various countries using dams and artificial water basins described above.

Extracting Tidal Energy: Non-traditional Approach

As mentioned earlier, all existing tidal power plants have been built using the conventional design developed for river power stations with water dams as their principal component. This traditional river scheme has a poor ecological reputation because the dams block fish migration, destroying their population, and damage the environment by flooding and swamping adjacent lands. Flooding is not an issue for tidal power stations because the water level in the basin cannot be higher than the natural tide. However, blocking migration of fish and other ocean inhabitants by dams may represent a serious environmental problem. In addition, even the highest average global tides, such as in the Bay of Fundy, are small compared with the water heads used in conventional river power plants where they are measured in tens or even hundreds of meters. The relatively low water head in tidal power plants creates a difficult technical problem for designers. The fact is that the very efficient, mostly propeller-type hydraulic turbines developed for high river dams are inefficient, complicated and very expensive for low-head tidal power application.

These environmental and economic factors have forced scientists and engineers to look for a new approach to exploitation of tidal energy that does

Table 3 Some potential sites for tidal power installations (traditional approach)

Country	Site	Potential power (MW)	Basin area (km²)	Mean tide (m)
USA	Passamaquoddy	400	300	5.5
USA	Cook Inlet	Up to 18 000	3100	4.35
Russia	Mezen	15 000	2640	5.66
Russia	Tugur	6790	1080	5.38
UK	Severn	6000	490	8.3
UK	Mersey	700	60	8.4
Argentina	San Jose	7000	780	6.0
Korea	Carolim Bay	480	90	4.7
Australia	Secure	570	130	8.4
Australia	Walcott	1750	260	8.4

not require massive ocean dams and the creation of high water heads. The key component of such an approach is using new unconventional turbines, which can efficiently extract the kinetic energy from a free unconstrained tidal current without any dams. One such turbine, the Helical Turbine, is shown in **Figure 2**. This cross-flow turbine was developed in 1994. The turbine consists of one or more long helical blades that run along a cylindrical surface like a screw thread, having a so-called airfoil or 'airplane wing' profile. The blades provide a reaction thrust that can rotate the turbine faster than the water flow itself. The turbine shaft (axis of rotation) must be perpendicular to the water current, and the turbine can be positioned either horizontally or vertically. Due to its axial symmetry, the turbine always develops unidirectional rotation, even in reversible tidal currents. This is a very important advantage, which simplifies design and allows exploitation of the double-action tidal power plants. A pictorial view of a floating tidal power plant with a number of vertically aligned triple-helix turbines is shown in **Figure 3**. This project has been proposed for the Uldolmok Strait in Korea, where a very strong reversible tidal current with flows up to 12 knots (about $6 \, \text{m s}^{-1}$) changes direction four times a day.

The following expression can be used for calculating the combined turbine power of a floating tidal plant (power extracted by all turbines from a free, unconstrained tidal current): $P_t = 0.5 \eta \rho A V^3$, where P_t is the turbine power in kilowatts, η is the turbine efficiency ($\eta = 0.35$ in most tests of the triple-helix turbine in free flow), ρ is the mass water density, A is the total effective frontal area of the turbines in m^2 (cross-section of the flow where the turbines are installed) and V is the tidal current velocity in m s^{-1}. Note, that the power of a free water current through a cross-flow area A is $P_w = 0.5 \rho A V^3$. The turbine efficiency η, also called power coefficient, is the ratio of the turbine power output P_t to the power of either the water head for traditional design or unconstrained water current P_w, i.e. $\eta = P_t / P_w$.

The maximum power of the Uldolmok tidal project shown in **Figure 3** is about $90 \, \text{MW}$ calculated using the above approach for $V = 12 \, \text{knots}$, $A = 2100 \, \text{m}^2$ and $\eta = 0.35$.

Along with the floating power farm projects with helical turbines described, there are proposals to use large-diameter propellers installed on the ocean floor to harness kinetic energy of tides as well as other ocean currents. These propellers are, in general, similar to the well known turbines used for wind farms.

Utilizing Electric Energy from Tidal Power Plants

A serious issue that must be addressed is how and where to use the electric power generated by extracting energy from the tides. Tides are cyclical by their nature, and the corresponding power output of a tidal power plant does not always coincide with the peak of human activity. In countries with a well-developed power industry, tidal power plants can be a part of the general power distribution system. However, power from a tidal plant would then have to be transmitted a long distance because locations of high tides are usually far away from industrial and urban centers. An attractive future option is to utilize the tidal power *in situ* for year-round production of hydrogen fuel by electrolysis of the water. The hydrogen, liquefied or stored by another method, can be transported anywhere to be used either as a fuel instead of oil or gasoline or in various fuel cell energy systems. Fuel cells convert hydrogen energy directly into electricity without combustion or moving parts, which is then used, for instance, in electric cars. Many scientists and
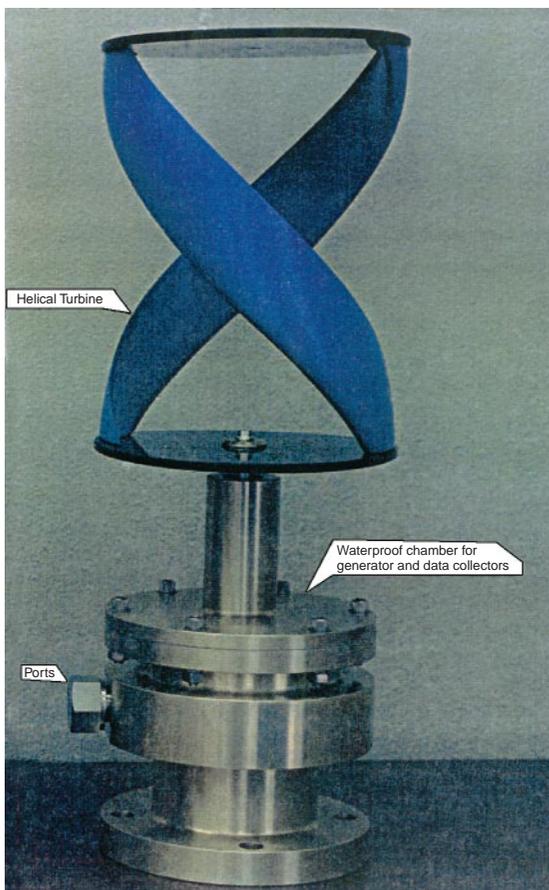

Figure 2 Double-helix turbine with electric generator for underwater installation.
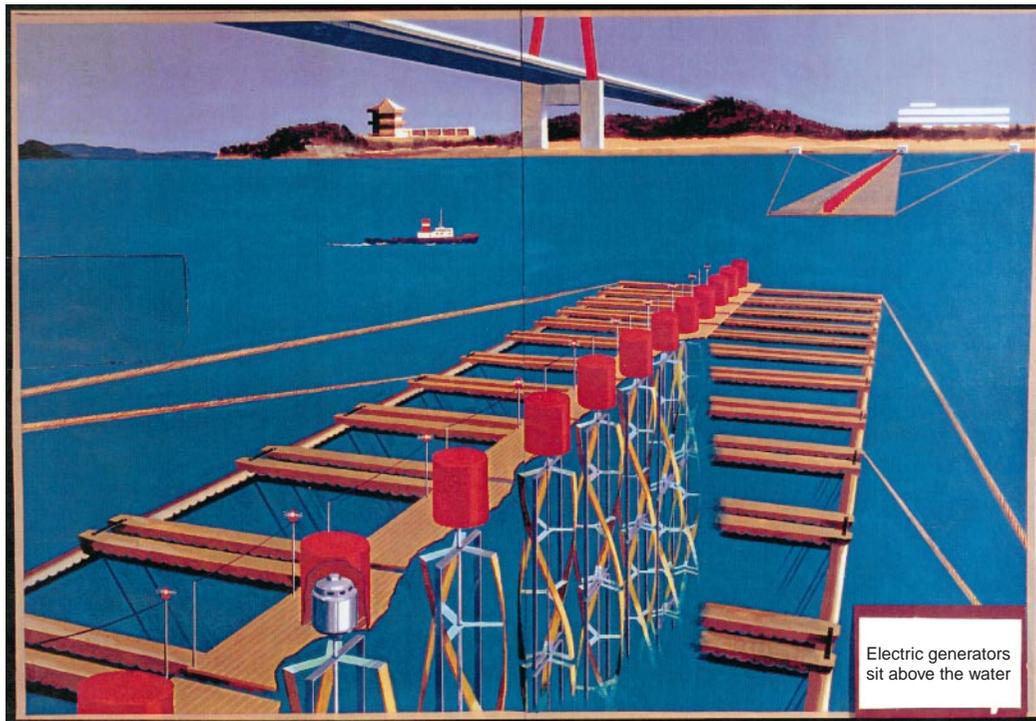
Figure 3 Artist rendition of the floating tidal power plant with vertical triple-helix turbines for Uldolmok Strait (Korean Peninsula).

engineers consider such a development as a future new industrial revolution. However, in order to realize this idea worldwide, clean hydrogen fuel would need to be also available everywhere. At present most hydrogen is produced from natural gases and fossil fuels, which emit greenhouse gases into the atmosphere and harm the global ecosystem. From this point of view, production of hydrogen by water electrolysis using tidal energy is one of the best ways to develop clean hydrogen fuel by a clean method. Thus, tidal energy can be used in the future to help develop a new era of clean industries, for example, to clean up the automotive industry, as well as other energy-consuming areas of human activity.

Conclusion

Tides play a very important role in the formation of global climate as well as the ecosystems for ocean habitants. At the same time, tides are a substantial potential source of clean renewable energy for future human generations. Depleting oil reserves, the emission of greenhouse gases by burning coal, oil and other fossil fuels, as well as the accumulation of nuclear waste from nuclear reactors will inevitably force people to replace most of our traditional energy sources with renewable energy in the future. Tidal energy is one of the best candidates for this

approaching revolution. Development of new, efficient, low-cost and environmentally friendly hydraulic energy converters suited to free-flow waters, such as triple-helix turbines, can make tidal energy available worldwide. This type of machine, moreover, can be used not only for multi-megawatt tidal power farms but also for mini-power stations with turbines generating a few kilowatts. Such power stations can provide clean energy to small communities or even individual households located near continental shorelines, straits or on remote islands with strong tidal currents.

See also

Flows in Straits and Channels. Tides.

Further Reading

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