

Chapter 11

Power from the Water

Abstract More than two-thirds of the planet's surface is covered by water, and power may be obtained from both the surface water and the deep oceans. Hydroelectric, tidal, ocean current, wave, and OTEC power installations are among those that may convert the power of the water directly to electricity. Unlike wind power, these renewable energy sources are either continuous or predictably variable. The naturally occurring water cycle and the resulting rainfall transfer millions of tons of water annually to high elevations with significant potential energy. River flows on the planet carry the very high amounts of potential and kinetic energy, which currently turn the turbines of several hydroelectric power plants and have the capability to provide at least 25% of the total electric energy demand of the planet. The 240 MW tidal power plant in La Rance, France, has proven that there are reliable systems in operation to convert the tidal energy of the sea to electric power. Tidal power plants in prime locations in England, Norway, USA, Canada and other parts of the world have the capability to produce between 25 and 100% of the electricity demand in several coastal countries. The harnessing of the energy in ocean currents, such as the Gulf Stream, is at present a rather futuristic idea, which has the potential to cover the entire global demand for electricity. Several wave power systems and devices have been invented in the last half of the twentieth century, which are now in the testing and pilot-plant phases. If successful, harnessing the waves and the widespread use of wave power have the potential to produce more than 50% of the electric demand in island and coastal countries, such as Portugal, Norway, Great Britain, Japan, South Africa. and Australia. The Ocean Thermal Energy Conversion (OTEC) cycle also has the potential to supply almost unlimited electric power to coastal communities, but needs significantly more research and development efforts to reliably and economically meet this promise. All these electric power sources associated with the flow of water are examined in this chapter in a scientific manner. Engineering systems and cycles for the utilization of these resources are described. The environmental and ecological impacts of these systems are also examined critically.

11.1 Hydroelectric Power

The use of the potential and kinetic energy of water as a source of power has been known for thousands of years. Watermills were used in Asia and Europe to grind or mill the grain and produce flour. Today, similarly constructed plants transform the potential and kinetic energy of water to electricity. Figure 11.1 shows schematically how the potential and kinetic energy of the water may be transmitted to the prime mover, which is the shaft of the water wheel. In this case, if the torque on the water wheel is denoted by T and the angular velocity by ω , the total power recovered from the river flow is:

$$\dot{W} = T\omega. \quad (11.1)$$

When the water flow is not constant and predictable, or when relatively constant power is needed, a dam is built to restrict the flow of water upstream and create a water reservoir that maintains the water flow to the water wheel at a controlled rate. Damming the stream and the creation of the reservoir makes the water flow through the water wheel more predictable and reliable throughout the several seasons of the year. The dam also raises locally the level of the water surface, thus increasing the potential energy that may be converted to electric power.

The harnessing of hydroelectric power in contemporary power plants relies on the difference of the potential energy of the water and the mass flow rate of the water flow. The maximum amount of power that may be produced by a stream of water flowing at mass flow rate \dot{m} , when it falls over a height by Δz is:

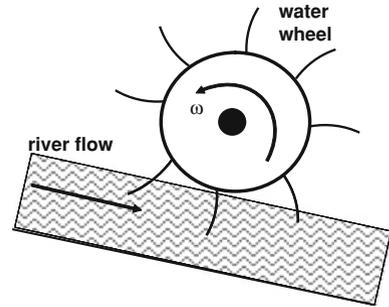
$$\dot{W}_{\max} = \dot{m}g\Delta z. \quad (11.2)$$

A schematic diagram of a typical hydroelectric power plant is shown in Fig. 11.2. A river with relatively high mass flow rate is restricted by a dam, close to a point where a significant drop in elevation occurs. Locations close to a waterfall or near water rapids are excellent candidates for the building of dams. The dam creates an artificial water reservoir upstream, which may store several billions or trillions of tons of water.¹ Because of their large size, the capacity of the artificial reservoirs is measured in acre-feet. One acre-foot is equal to 326,000 gallons or 1,239 m³. Water from the artificial reservoir enters a large pipe, the *penstock*, and is directed to a system of hydraulic turbines, which produces electric power. The water discharge from the turbine is directed to the same river, downstream. Frictional and other losses in the penstock are typically very small. The actual work produced by the hydraulic turbine is lower than the maximum work because of the finite efficiency of the turbine, which is typically in the range 72–84%:

$$\dot{W} = \eta\dot{m}g\Delta z \quad (11.3)$$

¹ One cubic meter of water contains approximately 1 t, or 1,000 kg, of mass.

Fig. 11.1 Operation of a water wheel



A large hydroelectric power plant has several, typically 5–30, penstocks that lead to a number of turbines and operate in parallel to produce power. The river supplies the artificial reservoir and has sufficient water to maintain an approximately constant head, Δz .

From elementary thermodynamics it is known that the potential energy of fluids is very low (as specific energy in kJ/kg) in comparison to the thermal energy. One kg of water at 30 m height difference has specific energy ($g\Delta z$) equal to 0.294 kJ/kg. In comparison, one kg of steam has specific internal energy close to 3,000 kJ/kg, which is 10,000 times higher. Even when one considers the Carnot limitations of the thermal energy conversion, e.g. 30–40% practical overall conversion efficiency, the specific thermal energy of the steam is by far higher for the production of electric power. The very high power of the hydroelectric power plants is provided by the vast amounts of water, which are available in a river and pass through the several hydraulic turbines. Typical flow rates in large rivers are in the range 10^4 – 10^5 m³/s. Such flow rates bring the equivalent mass flow rates of 10^7 – 10^8 kg/s to the power plants. Simple calculations show that these hydroelectric plants with 75% turbine efficiencies will have the capacity to produce between 2,200 and 22,000 MW of electric power. For comparison, a typical nuclear power plant produces approximately 1,000 MW of electric power. Of course, smaller rivers with lower flow rates would produce a lower amount of electric power. Table 11.1 shows several of the largest hydroelectric power plants in the world and their power generation capacity. It must be noted that, with the exception of the “Three Gorges” plant in China, most of the other hydroelectric power plants are older installations, with some, e.g. Krasnoyarsk and Hoover Dam, operating continuously since the 1930s.

11.1.1 Global Hydroelectric Energy Production

The year 2009 statistics of the world total hydroelectric power installations are approximately 770,000 MW. The existing hydroelectric power plants have collectively the capacity to produce 6,745 TWh of electricity ($6,745 \cdot 10^9$ kWh) or

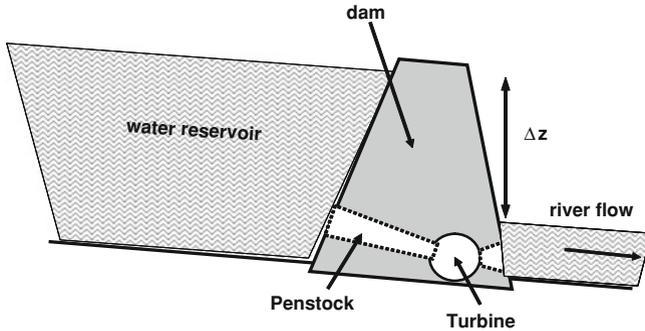


Fig. 11.2 A schematic diagram of a hydroelectric power plant

Table 11.1 Some of the largest hydroelectric plants in the world

Name of Plant	River/country	Power (MW)
Hoover dam	Colorado/USA	1,500
Niagara falls	Niagara/USA	1,950
Grand coulee	Columbia/USA	6,500
La grande	St Lawrence/Canada	10,000
Itaipu	Parana/Paraguay-Brazil	12,600
Three gorges*	Yangzee/China	18,200
Krasnoyarsk	Yenisei/Russia	6,400
Guri	Caroni/Venezuela	10,300

* Installed in 2009 and planned to increase to 22,500 MW by 2012

one third of the world's electric energy demand, which is approximately 20,000 TWh. In addition, several hydroelectric power plants have been constructed to provide electric power to a particular industry, typically an aluminum smelter, which requires very high amounts of electric energy for its operation. For example, the Brokopondo power plant in Surinam was constructed to provide electricity for the local Alcoa aluminum plant and the Manapouri Power Station in New Zealand was constructed to supply electricity to an aluminum smelter at Tiwai Point.

By reducing the flow to the turbines or by shutting down the flow through penstocks, the power produced by a hydroelectric power plant may be easily controlled and adjusted at short times. For this reason, hydroelectric power plants are used as intermediate and peak demand units (see [Chap. 12](#)) and many do not produce power continuously at their *rated power*. In 2009 approximately 3,200 TWh of electricity were produced from hydroelectric power plants. This implies that the average *plant capacity factor* of hydroelectric units was 47%. This is approximately 16% of the global electric energy demand and represents more

Table 11.2 Leading countries in hydroelectric power production

Country	Installed capacity, GW	Energy produced, TWh	Percentage of total electric energy
Brazil	69	364	86
Canada	89	370	61
P.R. China	172	585	17
India	34	116	16
Japan	27	69	7
Norway	28	140	98
Russia	45	167	18
Sweden	26	65	44
USA	80	251	6

than 90% of the electric energy from renewable energy sources. Table 11.2 shows the countries with the largest total installed hydroelectric capacity. Smaller countries, such as Norway have the capacity to produce their entire demand for electricity from hydroelectric power. However, this is not the case with larger electricity consumer countries, such as USA and the PRC, which produce 6 and 17% of their electricity from hydroelectric energy respectively.

Hydroelectric power plants may operate for a very long time if they are well maintained. The main mechanical parts, the turbines, may be frequently maintained, refurbished and replaced if necessary. Penstocks, valves, and water gates do not contain any moving parts and last much longer. What may limit the life of a hydroelectric power plant is the silting of the reservoir upstream the dam. There is a stagnation region in front of the dam, where water comes to a standstill, turbulence is significantly reduced and the small particles that constitute the silt fall to the bottom. Oftentimes the sedimentation process is assisted by particle flocculation, which produces coarser grains. The sedimentation/siltation process reduces the water storage capacity of the reservoir and, if untreated, may shut down the reservoir. Excessive siltation in hydroelectric reservoirs may be avoided by:

- a) Diverting part of the water close to the bottom of the river to cause sediment bypassing
- b) By special weirs
- c) By appropriate projects upstream that reduce soil erosion and particulate entrainment
- d) By periodic dredging of the reservoir.

A well-maintained water reservoir will last for more than 100 years and the corresponding hydroelectric power plant for an equal amount of time. This longevity makes the hydroelectric power plants one of the least expensive systems for the production of electricity.

11.1.2 Planned Hydroelectric Installations and Future Expansion

Except for the construction of an often costly dam, hydroelectric power plants are relatively simple in operation, inexpensive to construct and, most important, do not require fuel for the production of electricity. Our accumulated experience of the plants built early in the twentieth century proves that the large hydroelectric power plants will operate for more than 80 years with relatively low maintenance. For this reason, most of the large-scale hydroelectric power plants produce electricity at significantly lower cost than thermal power plants. Also, most of the prime, large-capacity hydroelectric resources in the OECD nations, e.g. Japan, USA, Norway, and Canada, have been utilized and power plants in such locations have been in operation for at least 40–50 years. In the future, almost all of the immediate expansion of hydroelectric power will occur in developing countries and especially in the Peoples Republic of China and the continents of South America and Africa. In addition to the “Three Gorges” power plant, which is in the final stages of completion, there are currently several other hydroelectric power plant projects in China totaling 70,000 MW. Planned hydroelectric capacity in Brazil and Argentina is close to 10,000 MW and the proposed project of “Grand Inga” in the Democratic Republic of Congo alone is expected to produce 40,000 MW.

In countries that have already utilized most of their large-scale resources, the construction of *small hydro* (less than 30 MW) or *micro hydro* (less than 1 MW) is the way to utilize a higher percentage of the hydroelectric resources and to produce more renewable electric power. These plants are regional and may serve a small community or a single industrial plant. A glance at Eq. (11.3) proves that a smaller river with volumetric flow rate $10^3 \text{ m}^3/\text{s}$ and elevation drop of 4 m has the potential to produce 39.2 MW and will actually produce 29.4 MW with typical turbine-generator pairs that have 75% efficiencies. Smaller units at rivers with volumetric rates 100–500 m^3/s would produce electric power in the range 3–15 MW. There is a multitude of locations in Europe, and North America, where such rivers/resources exist and where small hydroelectric power plants may be constructed to produce a higher amount of electric energy from this clean and renewable source. These small hydroelectric resources are abundant and their increased utilization for the production of electricity may quadruple the hydroelectric energy produced in the OECD countries, where all the other, large-scale hydroelectric resources have already been utilized. An additional advantage of such *small or micro hydro* units is that, because the units are typically very small, it is not necessary to construct large dams and, hence, their environmental and ecological impacts are minimal. Smaller hydraulic turbines are available to produce lower amounts of power in these units. Oftentimes, these smaller power plants may be combined with flood control, irrigation and recreation projects to enhance the utility and benefits of the entire project to the local community.

11.1.3 Environmental Impacts and Safety Concerns

Hydroelectric power is essentially a clean, renewable energy source. However, the construction of the hydroelectric power plants, especially those of very large scale, poses a few environmental problems: At first is the construction of the dam and the reservoir behind it. Dams often exceed 50 m in height and 20 m width and require a very high volume of material, primarily concrete, to construct them. For example, the construction of the Hoover Dam in Nevada, U.S.A. required as much concrete as a 3,200 km, four-lane highway. Secondly, the dam causes the flooding of a very large area behind it, which becomes the water reservoir. The flooding of the area upstream requires the displacement of communities, the abandonment of whole towns, and the relocation of inhabitants and businesses. The construction of the “Three Gorges” dam in China was for a long time a very controversial project because it resulted in the displacement of 1,240,000 persons and the abandonment of several towns. It also caused extensive ecological change and when it was built, it caused the flooding of several important cultural and archaeological monuments. Thirdly, the construction of the dams prevents fish migration and restricts the waterways. Several studies have shown that hydroelectric dams along the Atlantic and Pacific coasts of North America have reduced salmon populations by restricting the fish access to spawning grounds upstream the rivers. This ecological impact is mitigated by the installation of artificial “fish ladders,” where the fish are able to swim upstream in a bypass waterway. Because the turbines harm the salmon spawn, in several reservoirs along the Columbia River, young salmon is transported downstream by barges during the spawning season.

The generation of electric power alters the downstream water environment. Because of sedimentation and the passage of water through sieves, water exiting a turbine usually contains a very small amount of suspended sediment. This prevents the river bottom nourishment downstream with fresh sediment and may lead to the scouring of the river beds and loss of riverbanks. Because the power generation in the power plant fluctuates, the turbine gates are opened and closed several times a day. This results in frequent fluctuations of the river flow, which contributes significantly to the erosion of the river downstream. The dissolved oxygen content of the water is also reduced because of the rapid swirling flow in the turbines. This, in addition to water warming as it passes through the turbine systems, may endanger the fish population and the ecological systems downstream.

The environmental impacts of the hydroelectric dams and power plants are relatively few and benign in comparison to the impacts of the fossil fuel power plants. However, a significant safety concern is dam failures, which have resulted in several of the largest man-made disasters in the history of electric power production. The Banqiao Dam failure in Southern China resulted in a great flood, the deaths of 171,000 people and left millions homeless. The failure of the Vajont Dam in Italy, which was built in a geologically unstable region, caused the deaths of 2,000 people. In this respect, the smaller dams and small hydroelectric power

plants, which are touted for the future, create a lesser risk, because they contain a much smaller volume of water and they affect a smaller fraction of the population. However, even these small plants are not immune from failures and disasters and must be maintained meticulously. For example the Kelly Barnes small hydroelectric dam in the USA failed in 1967 and resulted in 39 deaths ten years after its power plant was decommissioned. Good design, correct construction in the right location and meticulous maintenance will, in general, help avoid dam failure and disasters. It must be noted though that this is not an unfailing guarantee of safety, because large dams are tempting industrial targets for terrorism and wartime sabotage. In the early twenty-first century, appropriate security measures to thwart terrorist activities and sabotage are becoming part of the maintenance operations in all the large dams in the OECD as well as in many developing countries.

11.2 Tidal Power

Tides are created because of the gravitational and kinematic effects due to the position and the combined motion of the Earth, the Moon and the Sun. The Moon, even though it has much smaller mass than the Sun, plays a more important role in the creation of tides because it is significantly closer than the Sun. The mass of the Moon “pulls” the ocean water masses in its direction and creates a “bulge” on the surface of the ocean. The effect of the Moon’s pull is modified by the effect of the Sun, as shown in Fig. 11.3. When the Earth, the Moon and the sun are aligned, the tides are amplified and are called *spring tides*. When the three bodies form a right-angle triangle the tidal effect is modulated and we have the *neap tides*. There are two periods of spring tides and two of neap tides during every Moon cycle, which lasts for approximately 29.5 days.

A simple analysis of the effects of the gravitational potentials of the Earth and the Moon on the surface of the Earth’s ocean may be made with the help of Fig. 11.4, which shows the combined effect of the Moon’s gravity on the surface of the ocean and the rotation of the Earth around its axis. When we consider an equipotential surface around the surface of the Earth and perform the force balance resulting from the gravitational forces of the Moon and the Earth on a unit mass of water, at the surface of the ocean, we will obtain the following approximate expression for the height of the ocean “bulge” at any point on the surface of the ocean:

$$h(\theta) = \frac{r^4 m}{M d^3} \left(\frac{3}{2} \cos^2 \theta - \frac{1}{2} \right), \quad (11.4)$$

where θ is the angle formed between the line that connects the centers of the Earth and the Moon and the line that connects the center of the Earth with the point under consideration.; M is the mass of the Earth; m is the mass of the Moon; r is the average radius of the Earth, which is approximately 6,387 km; and d is the

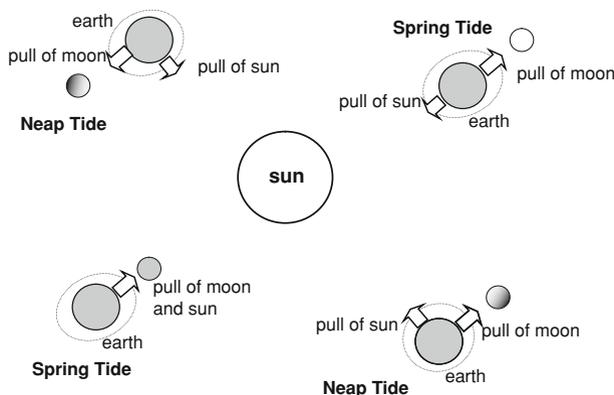
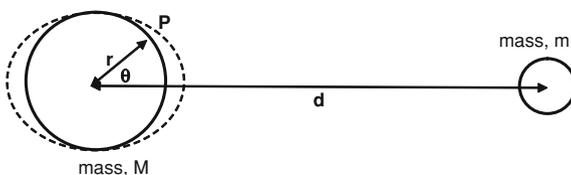


Fig. 11.3 Spring tides and neap tides

Fig. 11.4 Gravitational interaction of earth and moon



Moon to Earth distance, which is approximately 384,420 km. Given that $m/M = 0.0123$, Eq. (11.4) reveals that the maximum bulge on the surface of the oceans is 0.36 m. This value is close to the globally-averaged height of the tides on the oceans, which is measured to be approximately 0.5 m. The *range* of the tides, H , is the difference between the maximum and the minimum heights of the water. The average range of the surface of the oceans is twice the maximum height, or approximately 1 m.

The bulges on the tidal deformations on the surface of the ocean form the *tidal waves*, which are shallow, long wavelength waves that move on the surface of the Earth’s ocean. At any time, there are two highs and two lows on the surface of the ocean.

The Earth rotates around its axis with a period of 24 h, and the apparent motion of the moon is a rotation around the Earth with a period of 24 h and 50 min. This implies that the tidal waves propagate on the surface of the oceans with a period, which is half the apparent period of rotation of the Moon. Therefore, the period of the ocean tides is 12 h 25 min or approximately 45,000 s.

According to elementary wave theory, typical speeds of propagation of the tidal waves are close to 200 m/s. From the wave equation:

$$c = \lambda v = \frac{\lambda}{T}, \tag{11.5}$$

Table 11.3 Locations with high potential for tidal energy conversion

Location	Country	Range, m	Average Power (MW)	Annual energy, (GWh)
Cobequid	Canada	10.7	20,000	175,200
Passamaquoddy	Canada	5.5	1,800	15,768
Severn river	England	9.8	1,680	14,717
La Rance	France	8.4	349	3,956
Mont St. Michel	France	8.4	9,700	84,972
Kimberlay	Australia	6.4	630	5,519
Mesen (Mezen)	Russia	6.6	14,000	122,640
Khambat	India	7.0	7,000	61,320
Golfo Nuevo	Argentina	3.7	6,600	57,816

These numbers were calculated using the “one pool” tidal system according to Eq. (11.7)

one may conclude that the tidal wavelengths are approximately 9,000 km. This distance is greater than the width of the Atlantic Ocean and of the same order of magnitude as the maximum width of the Pacific Ocean.

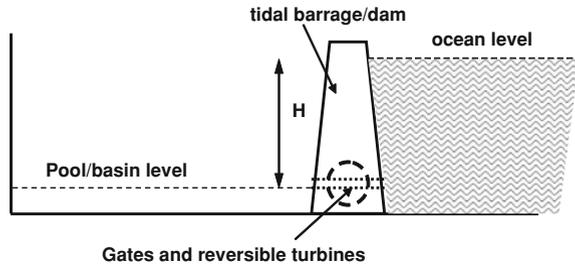
The presence of the continental shelves, the variable ocean depth and the irregularity of the coastlines interfere significantly with tidal waves and cause local distortions and resonances. The resonances create tidal waves with different amplitudes locally, which are significantly higher than the global average range of 1 m. These are most common in bays, gulfs and estuaries. Tidal ranges between 5 and 10 m have been observed in several narrow bays and estuaries. Several of these high ranges are listed in Table 11.3. These ranges reveal a few of the locations on the Earth with high potential for electricity production from tidal power.

Table 11.3 shows that the amount of tidal power, which is available for conversion to electricity, is very high. The average power available in several of the locations listed in this Table is equal to that produced by tens of conventional fossil fuel plants. For example, the power available in the Cobequid area alone is equivalent to 31% of the total electricity that was consumed in Canada in 2009. Similarly, the full utilization of the tidal power resources in France and England has the capacity to provide between 25 and 30% of the electricity consumption in the two countries. Clearly, tidal power if developed and well utilized may provide a high percentage of the electric energy demand and will prove to be an excellent alternative to fossil fuels.

11.2.1 Systems for Tidal Power Utilization

It is apparent from the above that, in every coastal location on the planet, the sea level is expected to rise and fall with a period of approximately 12.5 h or 45,000 s. Therefore, tidal power is a predictably variable, renewable energy source. Electric

Fig. 11.5 Single pool tidal system or tidal *barrage*



power may always be produced from tides in a predictable way. However, because this does not necessarily coincide with the variation of the electric energy demand tidal energy systems must be designed to store some or all of the energy that is available in tides.

A simple system to utilize the tidal power is the *tidal barrage* or *single pool tidal system* that is shown schematically in Fig. 11.5. The tidal barrage is essentially a dam that separates the ocean from a basin, which is typically a gulf or an estuary. Gates are located close to the bottom of the barrage and lead to hydraulic turbines. The latter operate at low pressure heads and are reversible. This implies that they produce power when the water flows in either direction. The gates are closed with the pool empty until the tide reaches the highest level, which is equal to the tidal range, H . At this instant the gates open, the turbines operate producing electricity and the pool fills with water. The total amount of energy produced during the filling of the pool from level 0 to H is:

$$W = \int \eta gh dm = \int_0^H \eta gh A \rho dh = \frac{1}{2} A \eta \rho g H^2, \quad (11.6)$$

where η is the average efficiency of the turbine, A is the cross sectional area of the pool, assumed to be uniform, and ρ the water density, approximately $1,000 \text{ kg/m}^3$. When the pool fills with water, the gates close, the level of the pool is at H and the plant does not produce electric energy. The level of the ocean drops until the low tide point is reached, when the pool is at level H above the ocean. At this instant, the gates open again and the reciprocating turbines produce power for the second time within a single tidal wave cycle. Hence, the single pool system produces twice the amount of energy shown in Eq. (11.6) during the approximately 12.5 hours of the period of the tidal wave. Therefore, the average power produced is:

$$\dot{W} = \frac{A \eta \rho g H^2}{T}, \quad (11.7)$$

where $T \approx 12.5 \text{ h} = 45,000 \text{ s}$.

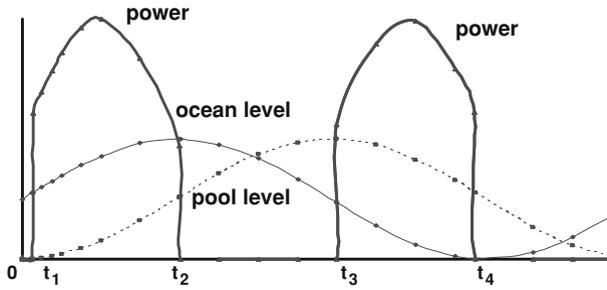


Fig. 11.6 Power production, ocean and pool levels in the single pool tidal system

It is apparent from this analysis that the single pool system does not produce power continuously. Rather, its operation produces this amount of power in two “bursts,” during the fast filling and emptying processes, which last approximately 20–30 min. The actual power produced during the short time of the power plant’s operation is significantly higher than that calculated from Eq. (11.7). For example, if the discharge occurs within 20 min (1,200 s), the actual power would be $45,000 / (2 \cdot 1,200)$ or 18.75 times higher than the average power indicated by Eq. (11.7). The system remains idle during the rest of time. This type of operation for the utilization of tidal power has several disadvantages including the following:

1. Very high power is only produced over very short periods of time, when the demand may not exist. In the absence of high electricity demand, the power level of other facilities will have to be reduced to accommodate the produced power. This may involve significant and undesirable power fluctuations in the other power plants that supply electricity to the electricity grid.
2. The system must employ very high power turbines to accommodate the “bursts” of power produced. The high-power turbines are significantly more expensive and add to the capital cost of the power plant and the final cost of electric energy.
3. Switching on and off the turbines, excitors, and generators adds significantly to the wear of the equipment and shortens their useful lives.

An alternative operation of the single pool system is to operate the turbines for longer periods of time and to shut them down only when the power produced falls below a minimum, predetermined value. The disadvantage of this type of operation is that the pool fills up and the difference in the level of the water may be significantly lower than H over the periods when power is produced. The turbines produce a lower amount of power and energy during the tidal cycle. The main advantage of this type of operation is that the tidal power plant uses smaller and less expensive turbines. In addition, other power installations are not unduly burdened by its operation. Figure 11.6 shows the operation of the plant as a function of time and the power produced by it. The upper part of the figure shows

the water levels of the ocean, $h_o(t)$, and that of the pool, $h_p(t)$. The instantaneous amount of work produced under this mode of operation is:

$$W(t) = A\rho\eta g \left| h_o^2(t) - h_p^2(t) \right|. \quad (11.8)$$

The total work produced during a tidal cycle is:

$$W = A\rho\eta g \left[\int_{t_1}^{t_2} |h_o(t) - h_p(t)| \frac{d|h_o(t) - h_p(t)|}{dt} dt + \int_{t_3}^{t_4} |h_o(t) - h_p(t)| \frac{d|h_o(t) - h_p(t)|}{dt} dt \right], \quad (11.9)$$

and the average power of the power plant is:

$$\dot{W} = \frac{2A\rho\eta g}{45,000} \left[\int_{t_1}^{t_2} |h_o(t) - h_p(t)| \frac{d|h_o(t) - h_p(t)|}{dt} dt + \int_{t_3}^{t_4} |h_o(t) - h_p(t)| \frac{d|h_o(t) - h_p(t)|}{dt} dt \right]. \quad (11.10)$$

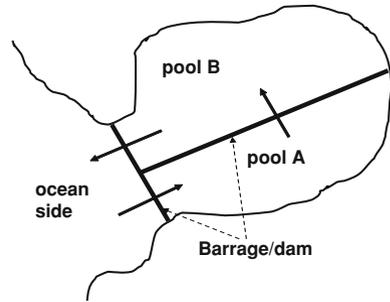
The two functions of the water height in the ocean and the pool, $h_o(t)$ and $h_p(t)$, may be approximated as sinusoidal functions. Hence, the total energy produced and the average power may be evaluated analytically or numerically. One of the characteristics of the single pool tidal system is that the choice of the time periods t_1 to t_2 and t_3 to t_4 , when the system is in the power-producing mode, may be appropriately chosen and optimized to suit electricity production objectives, such as maximum power generation or power production during peak demand.

The *two-pool tidal system* includes another controllable parameter for the optimization of power generation objectives by making use of an additional water pool where water may be discharged. The two-pool tidal system utilizes two water pools, which are filled and emptied during each tidal cycle. The system may be optimized in one of the following three ways:

- a) To produce the maximum amount of energy during a tidal cycle
- b) To produce maximum power during periods of peak demand
- c) To produce some power but also store energy for use during peak demand.

Figure 11.7 is a schematic diagram of the two pool system. At high tide, pool A is filled by the ocean water, thus producing some power, while pool B is at its lowest level and closed. When pool A is filled, it starts discharging to the low-level pool B, thus producing additional power. By the time the water level in the two pools A and B equalizes, the level of the ocean drops and both pools A and B may discharge their water to the ocean. Power is produced during this discharge phase. The capacities of the two pools may be chosen so that the effects of the gravitational head variability are minimized. This type of operation of the two-pool system results in continuous and almost uniform power generation.

Fig. 11.7 Operation of the two pool tidal system



It must be noted that, for the functioning of the two-pool system, it is not necessary to employ additional turbines than the single-pool system. Turbines are more expensive and add significantly to the cost of the installation. Instead of installing more turbines, one may construct a suitable network of pipelines, pen-stocks, inlets, outlets and diverting gate valves to always direct the flow from the higher water level to the lowest level, while passing the water through the same hydraulic turbines.

11.2.2 Environmental Effects of Tidal Systems

It is apparent from Table 11.3 that tidal power may produce a significant amount of electricity, thus replacing fossil-fuel power plants and avoiding the pollution effects associated with them. Tidal power is renewable, clean and does not emit any pollutants. There are some adverse environmental effects of tidal systems, which are enumerated here:

1. For the building of the pool systems, significant construction is required, which uses a great deal of materials, especially cement.
2. Dams and barrages pose an environmental hazard because they obstruct the passages of fish and other marine life.
3. Because the tidal systems are constructed in coastal environments, they invariably interfere with fish spawning and have an adverse effect on the populations of the fish and other aquatic life.
4. Because of the large water flows involved, there will be daily fluctuations in the turbidity and chemical composition of the water, which may have adverse effects on the aquatic life of bays and estuaries.
5. Local navigation of boats and recreational watercraft is adversely affected by the construction of barrages, dams and locks.
6. Additional sedimentation in the “pools” will necessitate frequent dredging and disposal of the, sometimes, contaminated silt.

On the positive side, the construction of a tidal system may have multiple purposes to add to the quality life in the surrounding communities. For example:

1. The upper surface of a barrage that connects two sides of an estuary may be paved and used as a road that connects communities.
2. Recreational activities, such as sailing, boating and swimming may be promoted within the enclosed estuary.
3. The additional construction may be used for flood control and avoidance of sea erosion.

11.3 Ocean Currents

Permanent ocean currents occur in several parts of the sea and are generated by a variety of forces including: the Coriolis force; the predominant surface wind; temperature and salinity gradients; the predominant tides. Variability in depth contours and shoreline configurations affect the ocean currents' direction and power potential. High intensity ocean currents are frequently met in the waterways between islands, at the tip of large peninsulas and capes, for example off Cape Hatteras in North Carolina, U.S.A. or at waterways that connect oceans, as for example the Strait of Magellan at the southernmost point of South America.

An ocean current is in all respects similar to a wind current. As with the wind power, the available power of ocean currents is given by the expression:

$$\dot{W}_{av} = \frac{1}{2} A \rho V^3 = \frac{\pi}{8} D^2 \rho V^3. \quad (11.11)$$

The power production limitation on wind power, or Betz's Law is also applicable to the ocean currents. The maximum power that may be produced from a water turbine, which is placed within the current, would be:

$$\dot{W}_{max} = \frac{8}{27} \rho A V_i^3 = \frac{2\pi}{27} \rho D^2 V_i^3. \quad (11.12)$$

A significant difference between wind and ocean currents is that the density of the water is approximately 800 times higher than that of air. This implies that significantly more power may be produced by water currents. For example a small ocean current turbine with 3 m blade diameter would produce a maximum of almost 152 kW of electric power. Such an engine would only produce 0.20 kW from the wind. As a result, sea current turbines may be significantly smaller and more compact than their wind counterparts.

Because water is dense and the volume of the water that circulates in the oceans is very large, if suitably utilized, ocean currents have a very high potential for the production of electric energy. For example, the *Gulf Stream* alone, which flows with a cross-sectional area of 100 km (62 miles) wide and 800 m (2,600 ft) to 1,200 m (3,900 ft) deep with average velocity 2 m/s, carries approximately

400,000 MW of power in the form of kinetic energy and may produce maximum power of 237,000 MW. If utilized continuously, the Gulf Stream energy would be sufficient to provide 50% of the electric energy consumption in the USA or 12% of the electricity consumed in the entire planet in 2009. It is evident that, tapping even a small fraction of this enormous potential resource to produce electricity would provide a significant amount of energy and replace the use of fossil fuels. In addition, because ocean currents are continuous, this form of renewable energy is not intermittent or predictably variable and ocean current turbines may be used for the continuous production of power.

While the use of ocean currents for the production of electricity is feasible and may prove to have significant payoffs, an ocean current power plant has not been built yet, even at a pilot scale. The principal impediments for such a project are:

1. Ocean storms and high currents that may damage underwater installations.
2. Transmission of electricity onshore and feeding into the national grid.
3. Lack of experience and pertinent research on underwater turbines and large-scale electricity generating systems, which must operate in a hostile, underwater environment.
4. Most strong water currents are in international waters. Lack of international treaties and governing laws increase the uncertainty and risk of investment.
5. Sabotage and terrorism concerns for systems that, by their very nature, are inherently built a large distance offshore.
6. Ecology, reproduction and migration of marine life.

11.4 Wave Power

The ocean waves are directly caused by the wind and, indirectly, from solar energy. Similar to the tide power, and because the oceans cover more than 70% of the Earth's surface, wave power is abundant and, if appropriately harnessed, it has the potential to provide a great deal of electric power.

11.4.1 Wave Mechanics and Wave Power

All waves are characterized by their: amplitude, α , which is half of the vertical distance between crest and trough; wavelength, λ , which is the horizontal distance between two successive crests; period, τ , which is the time at a point on the surface between two successive crests; and frequency $f = 1/\tau$. The wave velocity, c , is equal to λ/τ . When one follows the wave motion at a point on the water surface one sees that the physical fluid particles perform circular oscillations with period τ as shown in Fig. 11.8, with the wave velocity c superimposed on the physical velocities at the crest and the trough. From these considerations, we have the following expressions for the wave velocities at the crest and the trough:

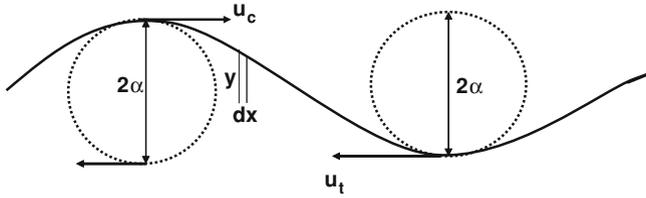


Fig. 11.8 Surface wave velocities

$$u_c = \frac{2\pi\alpha}{\tau} - c \quad \text{and} \quad u_t = -\frac{2\pi\alpha}{\tau} - c. \quad (11.13)$$

The pressure at the surface of the water is equal to the atmospheric pressure. When we apply Bernoulli's equation between the crest and the trough, we obtain the following expression:

$$u_t^2 - u_c^2 - 2g\alpha = 0. \quad (11.14)$$

The system of the last two equations together with the wave equation, $\lambda = c\tau$, yields the following expressions for the wave velocity, period and frequency:

$$c = \sqrt{\frac{g\lambda}{2\pi}}, \quad \tau = \sqrt{\frac{2\pi\lambda}{g}} \quad \text{and} \quad f = \sqrt{\frac{g}{2\pi\lambda}}. \quad (11.15)$$

The motion of the waves in the Cartesian coordinates may be expressed by a sinusoidal function, which has the form:

$$y = \alpha \sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{\tau}t\right). \quad (11.16)$$

For the calculation of the potential energy of the wave, let us consider a length of the wave, L , in a direction perpendicular to the direction of wave propagation. Referring to Fig. 11.8, the infinitesimally small volume, defined by the width dx , height y and length L has a potential energy equal to:

$$dE_P = \rho g \frac{y}{2} dV = \frac{1}{2} \rho g L y^2 dx. \quad (11.17)$$

One may substitute for the height y from Eq. (11.15) and integrate this expression over the entire wavelength of the wave, λ , to obtain the total potential energy in one whole wavelength as follows:

$$E_P = \int_0^\lambda dE_P = \frac{1}{2} \rho g L \int_0^\lambda \alpha^2 \sin^2\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{\tau}t\right) dx = \frac{1}{4} \rho g L \lambda \alpha^2. \quad (11.18)$$

It is known from wave theory that the total wave energy is equally partitioned between the potential and kinetic energy of the wave, that is $E_P = E_K$. Therefore, the total wave energy is twice the amount of the potential energy, which is expressed by Eq. (11.18):

$$E_T = E_P + E_K = \frac{1}{2} \rho g L \lambda \alpha^2. \quad (11.19)$$

The total wave power is equal to the product of the total energy and the wave frequency. Thus, the total power may be written as follows with the help of the expressions in Eq. (11.15) as:

$$\dot{W} = E_T f = \frac{E_T}{\tau} = \frac{\rho L \alpha^2 \lambda^{1/2} g^{3/2}}{8^{1/2} \pi^{1/2}} = \frac{\rho L \alpha^2 g^2 \tau}{4\pi}. \quad (11.20)$$

Oftentimes, the power per unit width and the power per unit area, or power density, are used for the computation of the total wave power. Since the width is L and the surface area is $L\lambda$, these two parameters may be calculated as follows:

$$\begin{aligned} \frac{\dot{W}}{L} &= \frac{\rho L \alpha^2 \lambda^{1/2} g^{3/2}}{8^{1/2} \pi^{1/2} L} = \frac{\rho \alpha^2 \lambda^{1/2} g^{3/2}}{8^{1/2} \pi^{1/2}} = \frac{\rho \alpha^2 g \sqrt{g \lambda}}{\sqrt{8\pi}} \\ \frac{\dot{W}}{A} &= \frac{\rho L \alpha^2 \lambda^{1/2} g^{3/2}}{8^{1/2} \pi^{1/2} L \lambda} = \frac{\rho \alpha^2 g^{3/2}}{8^{1/2} \pi^{1/2} \lambda^{1/2}} = \frac{\rho \alpha^2 g \sqrt{g}}{\sqrt{8\pi \lambda}}. \end{aligned} \quad (11.21)$$

Typical power densities per unit width of waves near the shores of the Atlantic and Pacific oceans are in the range 20–80 kW/m. Since the wave amplitudes are increased significantly during storms, the wave power varies from these levels to much higher values. For this reason, any system that would convert the wave energy to electricity must also be able to withstand the high forces and high power levels associated with high storm waves.

11.4.2 Systems for Wave Power Utilization

Everyone who has observed the waves on the sea or a lake has noted that the waves on the surface waters are actually formed by the superposition of several types of waves with different wavelengths, frequencies and speeds. As a result, the appearance of the sea surface is significantly more irregular than that of a sinusoidal wave. One can also see that most of the wave energy is contained in the long-wavelength, high-amplitude waves. While devices designed for the utilization of the sea waves should respond to and be able to absorb the energy from all the constituent wavelengths, for maximum energy production, these systems must be able to absorb efficiently the energy of the more energetic, high wavelength and high-amplitude waves. Several devices have been developed in the last half

Fig. 11.9 Schematic diagram of the *salter duck*

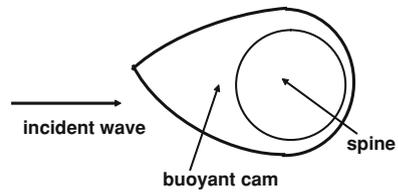
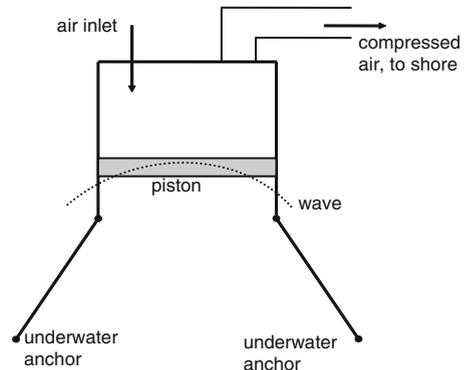


Fig. 11.10 Inverted piston-in-cylinder wave engine



century for the utilization of the sea wave power with various degrees of success. Among these devices are the following.

The *Salter Duck* was developed in the 1960's and took its name because its up and down motion resembles that of a duck in the water. It consists of a central cylindrical spine, around which is positioned a buoyant cam with a conical prismatic shape, as shown in Fig. 11.9. The cam is positioned so that its leading edge is in the principal direction of the incident waves. The shape of the cam is such that it responds to the motion of the incident waves, but it does not disturb the flow behind. The cam absorbs the energy of the incoming waves without creating any other waves on the lee side and converts the wave motion to its own motion, which in turn is transmitted to the prime mover of an electric generator.

Another, simple mechanism to harness the up-and-down motion of the waves is to use the inverted cylinder and piston assembly, which is depicted in Fig. 11.10. The wave action moves the buoyant piston in a vertical motion. When the piston moves downwards, a valve opens at the top and allows air to flow into the cylinder. When the motion of the piston is reversed, the inlet valve closes and the confined air is compressed until a predefined pressure is reached. At this moment the outlet valve opens and the compressed air is directed to a duct, which carries the compressed air to a power producing turbine, usually located onshore.

Another wave system utilizes the splashing effect of the waves on shores, which, by raising the level of the water periodically, results in the flooding of narrow parts of the coastline. This effect, essentially converts the vertical motion of the wave to an almost horizontal motion of the water on the shore, thus creating

a low-level, high-frequency tide. The horizontal motion may be converted to power by a waterwheel or a low-head water turbine. The velocity of the water is amplified by the use of a tapered channel, which directs the sea water of the wave to the low-head turbine. The TAPCHAN (tapered channel) system that was developed in Norway results in a 3–5 m elevation of the water level. This is a sufficiently high head to operate a small Kaplan turbine.

A fourth system, which has been proposed for ocean waves far from the shore, is the *Dam-Atoll* system, which is named from the combination of the actions of dams and atolls. The latter are small islands of volcanic origin. As the long-wavelength waves approach an atoll, they wrap around the small island and create a vortex with a significant spiral motion. The water is directed to the center of the Dam-Atoll system and its spiral motion drives a turbine, which is located at the center of the system. Because the Dam-Atoll systems float on the water, they may withstand strong sea storms. It has been estimated that an 80 m diameter, 20 m high Dam-Atoll system would produce approximately 1–1.5 MW power. For maximum power production, the Dam-Atoll systems must operate far from the shore. This presents the technical problem of power transmission to the shore.

11.4.3 Environmental Effects of Wave Power and Other Considerations

Wave power is clean, renewable, almost continuous, and does not pollute the atmosphere. Because the wave systems are built in the open seas, they do not affect the environment and the ecology of the coastal areas as much as tidal systems. The following are the most important environmental effects of the conversion of wave power to electricity:

1. Because the wave power density is relatively low, the wave conversion systems are massive and require large quantities of materials for their construction.
2. Most wave power systems are lengthy. Therefore, the navigation of ships will be obstructed.
3. All wave power systems include moving parts, which would kill fish and other sea animals if they are trapped in the systems.

Mechanical systems for wave power conversion must operate in adverse conditions: First, the systems must operate and maintain their structural integrity under heavy and low seas, under storms, and calm weather. This imposes a large constraint on the size, the strength of the materials and the design of the systems, which must withstand a very high range of forces. Because of the very high density of water, the forces that sea-wave systems must endure are by far higher than those of the wind-power systems. Secondly, the salt in the sea water is corrosive to most materials, and any wave energy system must be designed around this constraint.

Thirdly, the anchoring systems are not fail-safe. Often, the anchors fail or drift and this may cause the failure or damage of the power system on the water surface. Fourthly, some systems, such as the Dam-Atoll systems, must be located far from the shore. This makes the transmission of the electric power produced problematic. Such systems are also more susceptible to damage from the strong storms and high waves that occur in the high seas. These are some of the reasons why wave power systems are expensive and there are not many systems in operation, other than experimental or pilot systems.

An advantage of future wave power systems is the high correlation between the predominant wind and high energy waves. A promising wave power site is usually a good candidate for the construction of towers that produce wind power simultaneously. The construction of both types of electric production units at the same location would bring advantages from economies of scale as, for example, common generators, transmission lines, and maintenance crews.

11.5 Ocean Thermal Energy Conversion (OTEC)

The concept of Ocean Thermal Energy Conversion is almost as old as the theory of heat engines. The OTEC concept is included in most elementary Thermodynamics textbooks as a demonstration of the consequences of the Second Law of Thermodynamics: In tropical latitudes, water at the surface of the sea may reach temperatures in the range 27–32°C. At the same time, and because the sunlight does not penetrate at depths below 30 m, water in the bottom of deep bays is colder and may be in the range 5–8°C. These conditions create the two heat reservoirs that are necessary for the operation of the elementary heat engine, which is depicted in Fig. 3.7. The warm sea water at the surface and the cold sea water at the bottom constitute the two heat reservoirs that are necessary for the operation of a heat engine. All that is needed is the engineering system that would make this heat engine operational.

From the outset it must be noted that the efficiency of the OTEC heat engine would be very small. Even if we take the extreme temperatures mentioned in the previous paragraph, 32 and 5°C, the Carnot efficiency of the OTEC cycle would be less than 9%. In contrast, the Carnot efficiencies of gas cycles, where the higher temperature is in excess of 1,500°C, are higher than 80% and those of the Rankine cycles are close to 70%. The inherently very low Carnot efficiency of the OTEC cycle implies that the actual efficiency of OTEC systems would be even lower. Thus, the expected range of actual OTEC power plants is in the range 1–2%. However, the amount of heat that may be extracted from the water of the oceans is almost inexhaustible and free. Despite the low expected efficiency, a successfully designed OTEC power system would be capable of providing significant amounts of electric power in an environmentally friendly way.

11.5.1 Two Systems for OTEC

One way to utilize the temperature difference in the oceans is to use a simple Rankine cycle with a refrigerant substance as the working fluid. A schematic diagram of the components of the Rankine cycle is shown in Fig. 3.8 and the thermodynamic, $T-s$ and $P-v$, diagrams of the cycle are shown in Figs. 3.9a and b respectively. A pump is used to pressurize liquid refrigerant (process 2–3 in the diagrams). The fluid is then directed to a heat exchanger at the surface of the sea, which acts as the boiler, and the refrigerant evaporates (process 2–3). The high pressure vapor is directed to a turbine, which produces power (process 3–4). Finally the vapor from the exit of the turbine passes through another heat exchanger, at the bottom of the sea, which acts as the condenser of the system (process 4–1). The condenser exhausts at the pump inlet and the cycle is repeated. A variation of this operation is to have the condenser close to the surface or onshore and to pump cold water from the bottom of the sea to the condenser, instead of directing the vapor to the bottom and then pumping the refrigerant liquid to the surface.

While the Rankine cycle is a simple way to convert the temperature difference of the sea water to electricity, having the two heat exchangers, each of which requires a finite temperature difference to operate effectively, is a significant drawback. When one allows for a reasonable temperature difference in each heat exchanger, typically 5–10°C, the range of temperature that becomes available for the operation of the working fluid is very narrow and the Rankine cycle is not practical to operate. Also the two heat exchangers typically have very large areas because a great deal of heat must be transferred through them in comparison to the power produced. Assuming an average cycle efficiency of 2%, an optimistic figure given all the constraints of the cycle, the boiler of a 1 MW OTEC power plant must exchange 50 MW of heat with the sea water. Similarly, the condenser must reject 49 MW of heat, which implies that the two heat exchangers would have very large surface areas. In addition, any surface fouling of the heat exchangers would adversely affect the rate of heat transferred to the detriment of the electric power produced.

The *Claude cycle* was developed by Georges Claude, who actually built an OTEC power plant in Matanzas Bay, Cuba in 1929. This cycle does not use any heat exchangers and uses as the working fluid water vapor, which is produced from sea water. It is an open cycle similar to the *single flash cycle* used with the geothermal power plants. A schematic diagram of this cycle is shown in Fig. 11.11 and the corresponding $T-s$ diagram of the cycle is shown in Fig. 11.12. Warmer water at state 1 enters the low-pressure evaporator where it flashes and releases vapor at state 2. The produced vapor, at state 2'', is separated by gravity from the liquid water, at state 2', and is directed to the turbine, where it expands to the lower pressure of the condenser and reaches state 3. The expanded steam enters a direct-contact condenser, where it condenses to state 4 and is pumped back to the

Fig. 11.11 Schematic diagram of the Claude cycle for OTEC

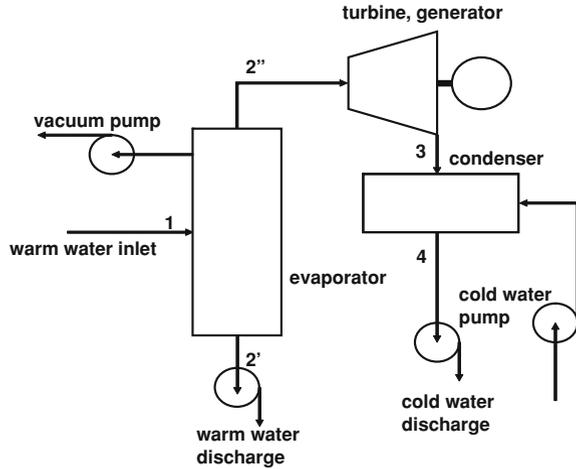
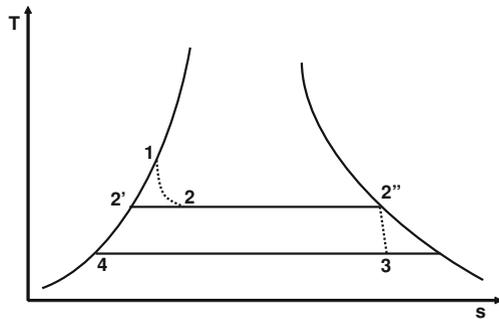


Fig. 11.12 Thermodynamic T-s diagram of the Claude cycle. The states of the working fluid correspond to the states in Fig. 11.11



sea. The remaining warm liquid water at state 2' is also pumped out of the evaporator.

The evaporator, where the flashing occurs, may be modeled as an adiabatic system, because any heat transfer from this equipment is negligible in comparison to the enthalpy of the warm water that enters. Applying the First Law of Thermodynamics to the evaporator, we may calculate the amount of vapor produced per unit mass of the water flow rate:

$$h_1 = (1 - x_2)h'_2 + x_2h''_2 \Rightarrow x_2 = \frac{h_1 - h'_2}{h''_2 - h'_2} \tag{11.22}$$

Furthermore, and since the specific work of the turbine is $h_2'' - h_3$, the total power produced by the Claude cycle is:

$$\dot{W} = \dot{m}x_2(h''_2 - h_3), \tag{11.23}$$

where \dot{m} is the entire mass flow rate that enters the evaporator at state 1. The flashing temperature, T_2 may be determined by maximizing the amount of power produced by the OTEC cycle. As with the geothermal flashing cycles, in an optimized Claude cycle, T_2 is approximately equal to the average of T_1 and T_3 .

The Claude cycle necessitates the use of several pumps that require a significant amount of auxiliary power. Theoretical efficiencies of this cycle may be as high as 4%, but the practically achieved efficiencies are not expected to be more than 1–2%. One of the advantages of the Claude cycle is that the machinery does not need to be anchored and may operate aboard a ship. The produced power must then be transmitted onshore by a cable.

11.5.2 Environmental Effects of OTEC and Other Considerations

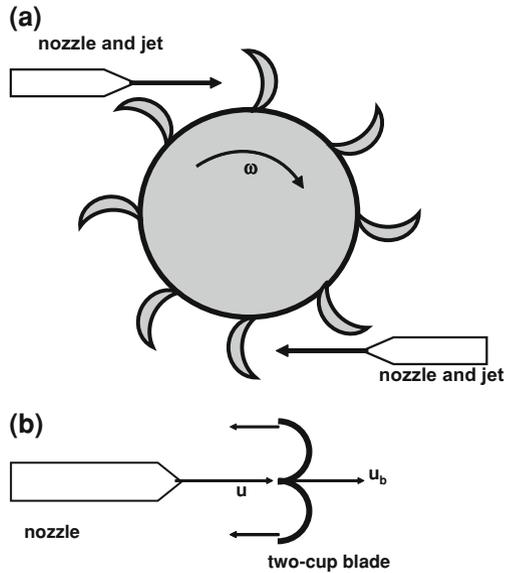
OTEC is another form of clean and renewable energy, which does not cause atmospheric pollution. Because the relative temperature differences between surface and sea-bottom water are present throughout the year, OTEC may become a continuous and rather reliable source of electric power. There are very low-impact and rather insignificant environmental and ecological effects associated with electricity production from OTEC, namely the local disturbance of aquatic life and, possibly, small impediments in the local ship navigation. Because the warm OTEC resources exist primarily in smaller bays, all environmental and ecological effects are localized in the vicinity of the OTEC power plant.

All OTEC cycles suffer from the inherent disadvantage of the low temperature differences and the implied low thermodynamic efficiencies. For this reason, all processes must be optimized and the equipment must be maintained in good condition. This becomes problematic in the ocean/coastal environment: Salty water causes corrosion and deterioration of the equipment, while the growth of algae tends to foul the fast heat exchanger surfaces, pipelines, and submerged water pumps. These are the main reasons why the few OTEC pilot plants that were built on shore or on barges have failed and were decommissioned after a few months of operation.

11.6 Types of Water Power Turbines

Water turbines are the most important energy conversion equipment in hydroelectric, tidal and ocean current power plants. Water power could not have been utilized at its present rate if it were not for the modern water turbine. The characteristics of water power are such that the water turbines must be versatile and must operate at low as well as at high heads ($g\Delta z$) as well as at low and high power

Fig. 11.13 **a** Schematic diagram of the Pelton wheel.
b Schematic diagram of the two-cup blades of the Pelton wheel



outputs. Two basic types of water turbines the *impulse turbines* and the *reaction turbines* are employed for water power conversion. The impulse turbines utilize solely the kinetic energy of the incident fluid for the production of power, while the reaction turbines utilize primarily the higher static pressure of the fluid.

The *Pelton wheel* is a typical impulse turbine. Figure 11.13a shows a schematic diagram of the Pelton wheel, which for all practical purposes is a waterwheel with specially designed water caps. Two high velocity water jets ensuing from diametrically opposed nozzles strike the blades of the Pelton wheel in opposite directions. The velocity of the water jets is controlled by varying the exit area of the nozzles with spear valves. The blades of the Pelton wheel consist of two cups that are joined at one end and are designed to deflect the water by 180° and, thus, achieve the maximum possible change of the momentum of the incident water jet. A more detailed schematic diagram of the blades, which includes the water velocities, is also shown in Fig. 11.13b.

Let us consider the water jet with a volumetric flow rate \dot{V} ensuing from the nozzle and moving toward the two-cup blade of the Pelton wheel. The absolute velocity of the jet is u . The blade also moves with absolute velocity u_b and, hence the velocity of the water relative to the blade is $(u - u_b)$. From mass conservation, the relative velocity of the water, as it leaves the blade is $-(u - u_b)$. Therefore, the total change of the water velocity relative to the blade is $-2(u - u_b)$ and the total change of momentum is $-2\rho\dot{V}(u - u_b)$. From the momentum conservation principle the latter must be equal and opposite to the force acting on the blade, that is:

$$F_b = 2\rho\dot{V}(u - u_b) = 2\dot{m}(u - u_b). \tag{11.24}$$

Since the blade moves with absolute velocity u_b , the power generated by the blade because of the jet action is:

$$\dot{W}_b = 2\rho\dot{V}(u - u_b)u_b. \quad (11.25)$$

For maximum power, the derivative of the last expression with respect to u_b must vanish. This condition yields $u_b = 0.5u$ and, hence, the maximum power generated by the jet may be calculated from Eq. (11.25) to be:

$$\dot{W}_{\max} = \frac{1}{2}\rho\dot{V}u^2. \quad (11.26)$$

A glance at the last equation proves that the maximum power that may be generated by a Pelton wheel is equal to the rate of kinetic energy carried by the water jet. The actual power generated by a Pelton wheel will be lower because of irreversibilities (primarily friction) associated with its operation. In practical operations, these irreversibilities are accounted for by the efficiency of Pelton wheels, which is in the range 75–80%.

Of the reaction turbines, the *Kaplan turbine* and the *Francis turbine* are not fully reaction turbines because they utilize both the pressure and the velocity of the incident fluid for the production of power. The impeller or runner of the Kaplan turbine resembles a propeller, while that of the Francis turbine is a spiral annulus, which diverts the water flow. The *degree of reaction*, R , defines the ratio of the specific energy of water that is converted into power to the total specific energy, e , converted²:

$$R = \frac{P_i - P_o}{\rho e} = 1 - \frac{u_i^2 - u_o^2}{2e}, \quad (11.27)$$

where the subscripts, i and o , denote the inlet and outlet of the turbine. The second part of Eq. (11.27) is a consequence of the application of Bernoulli's equation between the inlet and the outlet. One may also write the last part of Eq. (11.27) in the following form, which gives directly the specific energy of the water, $e = e_o - e_i$, which is converted to power in terms of the turbine inlet and outlet conditions.

$$\frac{P_i}{\rho} + \frac{u_i^2}{2} = e + \frac{P_o}{\rho} + \frac{u_o^2}{2}. \quad (11.28)$$

Regarding the choice of water turbines for specific applications, in general the Kaplan turbines are preferred in installations with high volumetric flow rates and low hydrostatic heads. Hydroelectric power plants with high volumetric flow rates and heads less than 50 m, would use Kaplan turbines. The Pelton wheel is ideal for

² The fluid energy in this case is actually equal to the exergy of the fluid and the difference, $e = e_o - e_i$, is the difference in exergy. For this reason, the symbol e is used for both quantities.

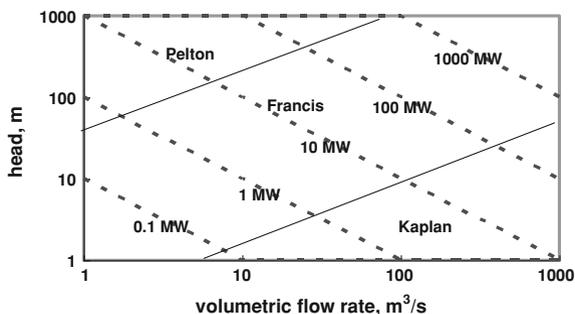


Fig. 11.14 Diagram for the choice of water turbines according to the volumetric flow rate and predominant water head

applications that involve high heads, up to 1,000 m, and low flow rates, less than 100 m³/s. For all conditions between these two limits, the Francis turbines are used, which can handle low volumetric flow rates at relatively low heads as well as high volumetric flow rates at relatively high heads. Figure 11.14, depicts a diagram for the typical uses of the three types of water turbines.

11.7 Concluding Remarks on Water Power

It becomes apparent, when one considers the several forms of water power, that this is a significant but underutilized energy resource. Despite the clear environmental advantages and the enormous potential of surface water to produce a significant percentage of the electricity demand, of the several types of water power plants that may be put in operation, only the hydroelectric power plants have been extensively used. There is significant technological expertise with hydroelectric power plants that extends to more than 120 years. The technology of these plants is considered proven and reliable. For this reason, the construction of large-scale hydroelectric power plants is expected to continue in the developing countries, including the emerging economies of India, Brazil, and the Peoples Republic of China. In the OECD countries, where most large-scale hydroelectric resources have been utilized, the next expansion of water power plants will take place with the small-scale and micro-scale plants, which have the capacity to contribute significantly to the electric demand of most countries.

However, the current situation and prospects are entirely different with the other types of water power conversion plants: Several prototype and pilot projects that utilize tidal, wave, and OTEC power have been built, but very few power plants that utilize these resources are currently in operation. Regarding ocean current plants, there have been several studies with good results but no actual projects. There are several economic, social, and technological reasons for this experience, some of which are summarized in the following paragraphs.

The primary reasons for the lack of more water power projects are economic and financial. Water power projects have long lives, very low variable costs (no fuel cost and low maintenance cost) but very high capital cost. The high capital cost associated with the construction of the massive dams, barrages, water turbines, wave engines, and OTEC plants are very high and must be amortized over the long life of the projects. In most of the cases, there have been no loan guarantees for the construction of these types of power plants and the owner or operator had to assume all the risks of the project. Therefore, any private corporation that undertakes the construction of a water power plant must place a great deal of capital and borrowing capacity at risk. In addition, lack of wide technological experience and available operational data with water power plants other than hydroelectric, makes the tidal, OTEC, wave, and ocean current plants high risk ventures, which are subject to very high insurance premiums. The high initial capital cost and insurance in general result in the high cost of the electricity produced by most water power plants, except from hydroelectric plants. It has become apparent with all water power projects that if individual pilot projects are not built first in the OECD countries, which have the capital structure and technology to build and put them successfully in operation, the very high potential of all water power will not be utilized in the entire world.

Tidal electric power production has had a significant success with the 240 MW power plant in La Rance, France. However, the low fossil fuel prices of the 1980s and 1990s have hampered the construction of more tidal power plants in other countries. Another tidal project across the English Channel in the Severn estuary, England, did not progress beyond a few feasibility studies. Despite the great promise, which is apparent in all the feasibility studies, there has not been a state or private entity that would undertake the construction of this project. The economic and financial reasons presented in the previous paragraph are the main reasons for the lack of more activity in tidal power.

The utilization of ocean water currents has not progressed beyond a few academic and feasibility studies. Lack of any operational expertise; the essentially unknown environment where ocean current sites are most energetic; and the risk-averse attitude of energy entrepreneurs contribute to the lack of any projects. Clearly, a great deal of research and development is needed in this technological area, which must come from state investment. One of the development areas is the construction of reliable underwater turbine-generator systems. Because of the very high potential of ocean current power on several sites worldwide, these ventures may prove very successful investments in the future, if their expected operational data are verified and validated at the feasibility stage.

Wave power has been produced by several experimental and pilot power plants at very small scale. A major deterrent of the further expansion of this type of power is the structural reliability of the equipment used and their survivability during major storms. A great deal of research and development is needed in the characterization and design of materials and equipment that would be used with wave power plants. There are currently several wave power engine designs and a few pilot projects on the coastal areas of England, Norway, and Ireland. If these

pilot projects prove to be successful and reliable in the near future, we will see a significant development of wave power before 2030.

OTEC power has received significant attention especially in USA and Japan. However, the few pilot plants that were built in the past have not proven to be reliable and were not successful in delivering their rated power continuously and for a long time. The main problem with the OTEC plants is equipment deterioration resulting from biological and chemical fouling and the structural reliability of the equipment with sea storms. In addition, the inherent very low power plant efficiencies limit significantly the power that may be produced from an OTEC installation. Despite the very high global potential of OTEC power and the fact that it is a continuous and very reliable energy source, expansion of OTEC activities are not expected to happen unless a significant technological breakthrough is achieved with the heat exchangers that are needed.

In conclusion, in the near future hydroelectric power is expected to play a more important role in the generation of electricity from renewable sources and will continue to be a viable and economic substitute for fossil fuels. Of the other water power sources, a few tidal power plants may be built on prime locations followed by several low-scale wave power pilot projects and demonstration plants. However, and despite their very high potential, it is rather unlikely that many ocean current and OTEC power plants will be built in the first part of the twenty-first century or that they will contribute significantly to the future global energy demand.

Problems

1. A small river is to be dammed to create a hydroelectric power plant. After the completion of the dam the river level will rise by 28 m. The river has a cross-sectional area 340 m^2 and the average water velocity is 0.6 m/s. If the combined turbine-generator efficiency of the power plant is 0.75, what is the power this river may produce?
2. The maximum water-level difference in the Three Gorges dam is 110 m. How much water flow rate (in kg/s and m^3/s) is required from the river to produce the rated power of the plant if the combined turbine-generator efficiency of the power plant is 0.76?
3. How much annual CO_2 emissions (in tons per year) would be avoided if the USA doubles its hydroelectric capacity and reduces the coal-fired power plants at the same time? The average overall thermal efficiency of the coal-fired power plants is 36% and the heating value of carbon is 32,700 kJ/kg.
4. Small waterfalls of 2–5 m exist in several locations on the planet. Typical water flow rates in these waterfalls are 2–100 m^3 . If you were to divert 50% of the water for electricity production, what would be the upper and lower range of the power that would be produced from such waterfalls? A typical efficiency of the turbine-generator pair is 75%.

5. If the proposed tidal power plant in Cobequid, Canada is to produce 20,000 MW of average power what would be the cross-sectional area of the dam to be constructed?
6. The average range of the tides in the Gulf of Mexico is 0.6 m (2 ft). It is proposed to construct a 1.5 MW tidal power plant for the process of fish and shrimp. If the height of the barrage is not to exceed 0.7 m, what would be the length of the barrage?
7. In several places the Gulf current is equal to or exceeds 4 knots. If a small water turbine with blade diameter 3.2 m were placed in these, what would be the maximum power this turbine would produce? How many of these water turbines are required to produce the equivalent of one typical nuclear power unit (1 GW)?
8. It is proposed to place 5,000 small water turbines with blade diameters 3.5 m at the bottom of the ocean and inside the Gulf stream, where the average velocity is 2 m/s. What is the maximum power these turbines would produce? What type of engineering and technological difficulties do you expect this scheme may have in the short- and the long-run?
9. The waves in the North Sea have average amplitude 3 m and wavelengths 30 m. What is the total power of these waves, the power per unit width and the power per unit area?
10. Waves of 30 m height and 60 m wavelength have been observed during adverse weather conditions in the Gulf of Mexico (e.g. during hurricanes and tropical storms). What are the total power and the power per unit area for these waves? What are the engineering problems that would be encountered in harnessing these waves?
11. What is the maximum power that may be produced from an OTEC cycle when the upper temperature is 34°C, the lower temperature is 6°C and the cycle receives 180 kW of heat? How much heat is rejected from this cycle?
12. Refrigerant 134a is used as the working fluid in an OTEC power plant, which utilizes a simple Rankine cycle without superheat. The condenser is at 12°C and the boiling of R-134a occurs at 28°C. The efficiency of the turbine is 76%. What is the thermal efficiency of this cycle and how much heat input is required for the cycle to produce 0.5 MW?
13. What is the actual power that may be produced from an OTEC Claude cycle when the high water temperature is 34°C, the lower temperature is 10°C and the cycle receives 200 kW of heat?
14. “The oceans comprise more than 70% of the surface of the Earth and may provide an unlimited amount of power from ocean current and thermal-ocean energy. We simply have to invest in this vast potential and soon we will have energy independence.” Comment with an essay of 300–400 words.