Ocean Thermal and Geothermal Energy: An Overview of Technologies and Systems

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ABSTRACT

The Earth and the oceans have a natural temperature gradient between the surface and given depths. The natural temperature gradient is used to operate renewable energy systems, such as power generation and space heating/cooling, which operate on similar thermodynamic concepts. For a given purpose, different technologies are used to extract heat from the two resources. Even though the concepts of the two systems are the same, their heat energy extracting performance is different. An overview of the similarities between the usages of the two thermal resources is presented in this paper. The energy balances at the surface of the Earth and the oceans are also presented.

1. INTRODUCTION

The Earth and the oceans store a lot of thermal energy that can be extracted for useful purposes. The major source of thermal energy for the oceans is the Sun. The Earth receives its geothermal energy from radiogenic heat generated from radioactive decay underground and from heat released as the earth cools down, whereas shallow geothermal energy is mostly received from the Sun.

The heat transfer processes at the surfaces of the Earth and the oceans maintain their respective energy balances, thus preventing global temperature changes. Thermal energy from these two resources can be used to produce electricity or used directly for other purposes, such as space heating or cooling of built structures. The systems used to extract thermal energy from both resources are similar, with similar thermodynamic concepts. However, the efficiencies of the systems are very different due to the different heat source temperatures.

The ocean has a large reservoir of thermal energy as a source of heat at the surface and a large reservoir of cold water as a heat sink. Deep geothermal energy conversion systems mostly use two major sources of heat: hydrothermal reservoirs and hot dry rock (HDR). Deep geothermal energy is used for power generation while shallow geothermal energy is used for direct or non-electric applications.

This paper provides an overview of the thermal resource of the Earth and the oceans and the systems used to extract the thermal energy.

2. ENERGY BALANCES AT THE SURFACES OF THE EARTH AND THE OCEANS

Significant heat exchange processes across the ocean surface are represented in an energy ocean budget. The rate of heat gain or loss, $Q_T$, by a given column of ocean water with a unit horizontal cross sectional area can be expressed as the difference between the total heat coming from the Sun and the total thermal energy loss from a given area (Bowden, 1983):

$$Q_T = Q_S - Q_b - Q_h - Q_e - Q_u$$

(1)

where $Q_S$ is the rate of heat absorbed by the ocean from incoming solar radiation, $Q_b$ is the rate of heat loss by back radiation, $Q_h$ is the sensible heat loss by convection and conduction, $Q_e$ is the rate of heat loss by evaporation from the ocean surface, and $Q_u$ is the thermal energy transported by ocean currents moving out of the given area (Saur, 1956). The $Q_b, Q_h$ and $Q_e$ terms could be either positive or negative depending on whether thermal energy is gained or lost by the given area. However, for the ocean as a whole, $Q_u$ is taken as zero because it only accounts for the redistribution of thermal energy within the ocean (Open University, 2001).

The thermal energy in the oceans is distributed around the globe by moving ocean currents. Ocean currents are mostly driven by solar energy and the Earth’s rotation. The circulation of waters in the oceans helps to distribute the thermal energy in the equatorial regions to certain areas in the polar regions (Emiliani, 1981). The equatorial regions receive much more heat from the Sun than the polar regions because of the different angles at which the sunlight strikes the Earth.

Heat lost by back radiation from the surface of the ocean increases with decreasing altitudes of the Sun. The heat loss by evaporation is higher close to the equator and decreases with increasing latitudes. Heat lost by convection and conduction has seasonal and regional variations, and depends on the temperature difference between the ocean surface and the air close to the surface. A more detailed explanation of the heat budget terms are provided by Faizal and Ahmed (2011).

Deep geothermal energy originates in the ground by the radioactive decay and from heat released as the Earth cools down, whereas shallow geothermal energy close to the ground is mostly stored solar energy. The heat exchange processes at the surface of the Earth can be represented in an energy balance (Radcilffe and Šimůnek, 2010):

$$R_n = S + \lambda ET + J_H$$

(2)
where $R_n$ is the net downward radiation to the soil, $S$ is the sensible or conductive heat flux representing the vertical transport of air between the soil surface and the air, $A$ is the latent heat of vaporization, and $ET$ is heat loss by evapotranspiration (evaporation plus plant transpiration). All the terms on the right side of Equation 2 are positive when energy is moving away from the surface (up into the air or down deeper into the soil) (Radcliffe and Šimůnek, 2010).

The main mechanism for heat transfer towards the crust from the core is conduction. Convection occurs as a result of water (mostly rainwater) motion that penetrates Earth from natural recharge. The water gets heated up by hot rocks and is collected into aquifers, forming hydrothermal reservoirs. Geothermal energy fields are a continuous circulation of heat and thermal fluids. The fluids enter thermal reservoirs through natural zones, and leave through discharge areas such as hot springs (Barbier, 2002).

When geothermal energy is extracted, new recharge areas are created to reinject fluid in the reservoirs. Reinjection helps in maintaining the reservoir pressure, replacing gaseous fluids with water, and leading to a sustainable use of the hydrothermal reservoirs. Waste fluids through industrial plants are also reinjected to the reservoirs (Barbier, 2002). Reinjection reservoirs are designed during early planning keeping in mind that the injection of fluids should not induce potential risks of cold water running to the production areas. Careful design decisions have to be made such as having reinjection reservoirs in field or outfield, depth of injection, injection costs, possible changes in reservoir temperature and pressure as a result of reinjection, temperature and chemistry of injected fluid (Kaya et al., 2011).

3. THERMAL RESOURCE OF THE EARTH AND OCEANS

The temperature of the ocean waters generally decreases with increasing depth (Figure 1a), except for polar regions. The upper layer of the ocean, approximately 50-200 m, has temperatures similar to the surface (26-28°C). Below the upper layer is a region of rapidly changing temperature known as the thermocline. This region extends approximately to a depth of 1000 m, after which the water temperature is cold (about 4°C) with almost negligible changes. The thermocline is the deepest in the tropics and shallower in the polar regions.

In the tropics, the temperature difference between warm and cold waters is maintained throughout the year with very few variations. Above the thermocline, there is an almost constant temperature heat source and below the thermocline there is an almost constant temperature heat sink (Avery and Wu, 1994).

The heat moves towards the surface of the Earth from the interior where it dissipates. This is proven by the existence of a geothermal gradient of 25-30°C/km of depth (Barbier, 2002). The temperature profile will vary with location and will be affected by the ground properties such as thermal conductivity. Heat, fractures in rocks, and the flow of geothermal fluids are fundamental elements of geothermal reservoirs. The fractures (or permeability) provide passages for convection, as well as providing connections between production and recharge wells. Near the surface, the ground temperature below a certain depth of the crust remains almost constant throughout the year. This is due to the fact that the effects of the surface temperature fluctuations diminish with depth due to the thermal inertia of the soil (Florides and Kalogirou, 2007).

The named layers of the Earth are the crust with approximate depth of 30 km, the mantle up to a depth of 2900 km, the outer core up to a depth of 5150 km, and the inner core up to 6370 km (Tony and Twidell, 2006). The temperature increases with depth and is approximately 5000°C at the inner core (Figure 1b).

4. TECHNOLOGIES FOR EXTRACTING HEAT ENERGY

The thermal energy from the Earth and the oceans can be extracted to produce electricity or for use in other non-electric purposes, such as space heating or cooling as discussed here. The systems operate on similar thermodynamic concepts, with differences in their performances due to the temperature of the heat source available for use.

4.1 Electricity Generation

The almost uniform temperature difference between surface and deep waters of the ocean can be used to operate Ocean Thermal Energy Conversion (OTEC) plants. These plants utilize the temperature gradient between warm surface water and deep cold water.
of the ocean to operate a low pressure turbine. These plants are more suitable for low latitudes (tropical oceans) because the water temperature remains almost uniform throughout the year with few variations due to seasonal effects.

Ocean thermal energy conversion power systems are basically divided into three categories: a closed cycle, an open cycle, and a hybrid cycle.

A closed cycle OTEC system (Figure 2a) incorporates a working fluid, such as ammonia or ammonia/water mixture, operating between two heat exchangers in a closed cycle. A closed cycle utilizes the warm surface water to vaporize the working fluid in a heat exchanger (evaporator). The vaporized fluid drives a turbine coupled to a generator. The vapor is then condensed in a heat exchanger (condenser) using cold deep seawater pumped to the surface. The condensed working fluid is pumped back to the evaporator and the cycle is repeated (Avery and Wu, 1994).

An open cycle OTEC system (Figure 2b) utilizes the warm surface water as the working fluid. The surface water is pumped into a chamber where a vacuum pump reduces the pressure to allow the water to boil at low temperature to produce steam. The steam drives a turbine coupled to a generator and then is condensed using deep cold seawater pumped to the surface.

The hybrid system (Figure 2c) integrates the power cycle with desalination to produce electricity and desalinated water. Electricity is generated in the closed cycle system circulating a working fluid and the warm and cold seawater discharges are passed through the vacuum chamber and condenser to produce fresh water.

The working fluids for either closed or hybrid cycles should be such that it is able to operate between the low temperatures and still give optimum efficiency. Mostly ammonia and ammonia/water mixtures are used. The cycle is a basic Rankine cycle that operates between a heat source and a sink to generate electricity with efficiency close to 3% (Nihous, 2007).

The power that the pumps need to do work is supplied from the gross power output of the OTEC power generating system. The cold water from the deep water is pumped up through a pipe. The cold water pipe is subjected to many forces such as ocean currents, drift of the OTEC platform, and the dead weight of the pipe. The pipe has to be designed and moored carefully to be able to withstand the many different forces acting on it in the open ocean.

Apart from generating electricity and producing fresh water, OTEC plants can be utilized for other benefits such as production of fuels such as hydrogen, ammonia, methanol, providing air-conditioning for buildings, on-shore and near-shore mariculture, and extraction of minerals (Huang et al., 2003).

To increase the thermal efficiency of the OTEC system, other kinds of energies such as solar energy, geothermal energy, industrial waste energy, and solar ponds can be introduced to increase the temperature difference (Yamada et al., 2006).

Deep geothermal energy conversion power systems are basically divided into three categories: dry steam, flash steam, and binary systems (Chamorro, 2012). Power systems are mostly suited for inlet geothermal fluid temperatures above 150°C. Binary systems can be used for inlet temperatures as low as 70°C.

Dry steam power plants (Figure 3a) are vapor-dominant, open loop systems that draw steam from the hydrothermal reservoirs. The steam directly passes through a turbine that drives a generator, after which it condenses and is reinjected into the thermal reservoir.

Flash steam power plants (Figure 3b) are open loop systems that extract a liquid-dominant mixture which then faces a sudden reduction in pressure in a flash vessel. This sudden reduction in pressure generates steam which is then passed through the turbine to generate electricity. The steam is then condensed and reinjected into the thermal reservoir.

In binary systems (Figure 3c), a working fluid with low temperature undergoes a closed cycle. The working fluid, such as ammonia or ammonia/water mixture, gains energy from the geothermal fluid in the evaporator and vaporizes to drive a turbine, after which it is condensed and is then pumped back to the evaporator in a closed cycle. The geothermal fluid, after passing through the evaporator and turbine is reinjected into the thermal reservoir in a closed loop.

Geothermal energy is mostly harnessed from hydrothermal reservoirs and hot dry rocks (HDR). Wells are drilled into the thermal reservoir to extract the geothermal fluids. The temperature and pressure of the fluids decide whether it can be used for electricity
For extracting thermal energy from HDR, a well is drilled to the depth where rocks are found and high pressure water is injected to open or create fractures. The water, which gets heated by the rocks, is brought to the surface to use for required applications. After extracting its thermal energy, the water is reinjected to the rocks to collect more energy in a cyclic process (Duchane, 1996). This water can be used for electricity generation or for direct applications. Hybrid cycles with fossil fuels or other renewable energy sources such as solar energy can be combined with geothermal power systems to increase performance of geothermal plants.

4.2 Other Non-electric Uses

Non-electric or direct application of ocean thermal and geothermal energy involves a wide variety of uses, such as space heating or cooling, aquaculture, health spas, agriculture, snow melting, mineral extraction and seawater desalination (Fridleifsson, 2001; Huang et al., 2003). Space heating/cooling is discussed here.

Heat pumps are basically used to heat or cool buildings by using the ocean thermal or geothermal energy as heat or sink. In winter the thermal energy in the oceans and the Earth is used as a source of heat, whereas in summer, the thermal energy is used as a heat sink. Figure 4 shows a schematic of building heating and cooling in summer and winter.

In summer, offshore water is drawn through pipes and passed through the condenser of the heat pump. The evaporator of the heat pump absorbs heat from the house and transfers to the seawater in the condenser. The seawater is then pumped back to the sea, whereas cooled fluid (air or water) is pumped in the building to meet the required human comfort (Zhen et al., 2007).

In winter, the seawater passes through the evaporator, transferring heat from the seawater to the house in the condenser, and then being pumped to the sea. Warm air or water is circulated in the building after being heated in the condenser of the heat pump (Zhen et al., 2007).

For space heating/cooling using shallow geothermal energy, the almost constant temperature at a given depth below the ground is used. The ground temperature varies with the air temperature at the surface up to given depths, after which an almost constant temperature is maintained throughout the year (Brandl, 2006). Figure 5 shows the ground temperature variation with increasing depth for tests done at Monash University, Melbourne, Australia. The temperature becomes almost constant with values of 16-18°C at 6 m depth. The thermal properties of the ground are required to design efficient heat exchanger systems (Kalogirou et al., 2012).

Ground sourced heat exchangers are used to heat or cool buildings by using the constant ground temperature as heat source or heat sink. There are two general types of heat exchangers: a) open systems and b) closed systems. In open systems, water from wells is
directly pumped to the heat pump to provide thermal energy for space heating or cooling. The groundwater is either injected back into the ground through a reinjection well, or disposed at the surface. In closed systems, a heat carrier fluid is circulated through high density polyethylene (HDPE) pipes. After absorbing or rejecting heat from the ground, the heat carrier fluid is pumped to the heat pump to provide thermal energy for space heating or cooling (Florides and Kalogirou, 2006). Figure 6 shows a schematic of an open system. The heat exchangers shown in Figures 7 and 8 are all closed loop systems.

![Ground temperature variations with depth measured at Monash University, Melbourne.](image)

Figure 5: Ground temperature variations with depth measured at Monash University, Melbourne.

The heat source/sink (Figure 4) can be connected to different types of ground heat exchangers. The heat exchangers are mostly HDPE pipes placed in boreholes, pile foundations, or placed horizontally in loops or straight lines close to the surface. These pipes absorb or reject heat from/to the soil through the use of the heat carrier fluid, which is mostly water/antifreeze mixture.

![Schematic of an open loop ground heat exchanger system.](image)

Figure 6: Schematic of an open loop ground heat exchanger system.

![Schematic diagram of a) borehole heat exchanger, b) energy pile system.](image)

Figure 7: Schematic diagram of a) borehole heat exchanger, b) energy pile system.
Borehole heat exchangers consist of HDPE pipes inserted vertically into boreholes, which are then filled with thermally conductive grout. Grout also supports the pipes and protects ground water contamination from possible leakages from the pipe (DeMoel et al., 2010). Figure 7a shows a schematic of a borehole heat exchanger for heating in winter.

Figure 8: Schematic diagram of horizontal ground heat exchangers.

Pile foundations or energy piles contain HDPE pipes in which the heat carrier fluid exchanges heat between the ground and the building through the use of a heat pump. The pipes are installed within the piles that are designed to meet the structural loads, thus no additional structural modifications to the piles are needed to meet the geothermal energy requirements (Brandl, 2006). Figure 7b shows a schematic of a pile foundation exchanging heat with a building in winter.

Horizontal ground heat exchangers are placed very close to the surface. The horizontal pipes occupy a lot of space. Since the pipes are very close to the surface, the heat carrier fluid will undergo temperature fluctuations since the ground temperature will be affected by the temperature of the air at the surface (Johnston, 2012). Figure 8 shows the layout of horizontal ground heat exchangers for heating in winter.

A hybrid heating and cooling system that uses both ocean thermal and geothermal energy can be used if the heating demands are very high. During heating mode, both ocean thermal and geothermal energies are utilized as heat sources. In cooling mode, the geothermal system is shut down and the ocean water serves as a heat sink. A schematic of this system is shown in Figure 9. The heat transfer to the heat pump from the ocean and geothermal water occurs with the aid of two heat exchangers. Geothermal water first transfers thermal energy to the water circuit feeding the evaporator of the heat pump. After exiting the evaporator, the water circuit gains additional thermal energy from the seawater before moving on to the geothermal heat exchanger, and thus the cycle continues (Mendrinos and Karytsas, 2003).

Figure 9: Schematic diagram of a hybrid system utilizing both ocean and geothermal energies for space heating or cooling (adapted from Mendrinos and Karytsas, 2003).

5. CONCLUSIONS

The surface energy balance and the thermal resource of the oceans and the Earth and systems for extracting these resources are presented in this paper. For oceans, the extracted energy is mostly balanced by natural processes such as circulation of water from polar regions to equatorial regions and energy from the Sun. The geothermal energy content of the Earth maintains its energy balance by getting energy from the Sun and from interior of the Earth, and by natural recharge of water in the soil through rainfall and through artificial recharging if thermal energy is extracted for useful purposes. The temperature of the oceans generally decreases with depth, whereas the temperature of the Earth increases with depth. The common uses of thermal energy from these resources are electricity generation and space heating/cooling of built structures. These systems follow the same concepts with
similar thermodynamic concepts. The performance for ocean systems using ocean thermal energy will be reduced since the temperature available for use less. Non-electric or direct use of the thermal energy for heating and cooling buildings uses a heat pump to obtain or discharge thermal energy from/to the ocean or the Earth. Shallow geothermal energy can be tapped using borehole heat exchangers, energy pile foundations, and horizontal pipes placed close to the surface. A combination of ocean thermal and geothermal energies can be used if the heating requirements are large.

REFERENCES


