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Energy from Low Temperature Differences

Brian K. Parsons

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Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

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Brian K. Parsons
Associate Engineer
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

ABSTRACT

A number of energy conservation and alternative energy approaches utilize a low temperature heat source. Applications in this category include:

- Solar ponds
- Ocean thermal energy conversion (OTEC)
- Low temperature solar thermal
- Geothermal
- Waste heat recovery and bottoming cycles

A general overview of low temperature power extraction techniques is presented and the differences between closed and open Rankine power cycles are discussed in detail. Specific applications and technical areas of current research in OTEC along with a breakdown of plant operating conditions and a rough cost estimate illustrate how the use of low temperature power conversion technology can be cost effective.

INTRODUCTION

Power extraction from low temperature differences is an area of interest in many renewable (solar), geothermal, and waste heat applications technologies. Similar temperature differences are being examined to increase the efficiency of fossil fuel and nuclear power plants. The potential for power production from low temperature difference power cycles is quite large. In the U.S. alone, the total technical market potential for bottoming cycles on industrial installations which existed in 1979 (not including power plants) exceeded 3 million kilowatts (Ref.1).

Over 3/4 of the solar energy incident on the earth is incident on the oceans. The majority of the radiation absorbed by the oceans is converted to thermal energy and the potential for OTEC has been estimated at up to 40,000 billion kilowatts. The temperature differences which are available for these cycles varies from 20°C for Ocean Thermal Energy Conversion (OTEC) up to 160°C for some geothermal and industrial processes. The electricity produced from these cycles may be routed into the power grid, used at other sections of the plant or converted to energy intensive materials such as ammonia or hydrogen.

In addition to the useful energy which may be extracted from low grade heat sources, reducing the outflow temperature from a conventional power plant is desirable from a thermal pollution standpoint. In many locations this fact may reduce both first costs and operating costs for cooling towers and other heat rejection equipment.

Ultimately, the decision to install a bottoming cycle on an existing facility or to construct power plants designed to utilize low temperature differences rests on economic viability and technical confidence. Economic viability is a function of component cost, resource availability and other factors. In most cases the value of the power produced is balanced against the capital costs of equipment and maintenance costs. Fuel costs need not be considered since the sun, the earth (geothermal) or plant outflow are used as the heat source. This paper will briefly discuss component costs for one type of system. It should be recognized that cycle feasibility analysis is highly dependent on local conditions. Even though many of the technologies associated with low temperature power production are similar to standard plants, new applications and variations are not as readily accepted by utility investors. A higher rate of return may be needed to first implement so called "unproven" technologies. Technical confidence is being improved by Department of Energy (DOE) programs in several technologies by testing components and their interactions in coupled systems.

POWER CYCLES

Description

Several thermodynamic power cycles have been utilized and/or proposed for low temperature use. The "Minto Wheel" (Ref.2) is a practical application of the Stirling Cycle in which a container filled with volatile fluid is immersed in the heat source. The fluid is vaporized and expands into another container immersed in the heat sink where it condenses. The gravitational force on the liquid filled container is used to rotate a wheel and generate power. A similar apparatus is used in an application of the Ericsson cycle (Ref.3). A closed container is immersed in a heat source. As the vapor evaporates, the container is allowed to expand. When immersed in the heat sink, the container contracts. If several containers are situated on spokes of a wheel, the resulting difference in buoyant force causes rotation. These two cycles have been analyzed for low temperature cycles (Ref.4), and are more applicable to temperature differences at the high range of bottoming cycles (150^{o}C). This paper will discuss applications of the Rankine cycle and a "lift" cycle which are areas of current research at the Solar Energy Research Institute (SERI) and other institutions investigating the ocean's thermal difference for power production. Figure 1 is a schematic representation of the cycles.

The Rankine cycle is used in nearly all existing power plants. Two types of Rankine cycle may be applied to low temperature power production, a closed loop system which uses a secondary working fluid and an open system in which water is used as the working fluid. In the closed cycle, warm water from the heat source is passed through a heat exchanger. Heat is transferred to a secondary fluid which evaporates. The vapor is then passed through a turbine which is connected to a generator. The vapor then condenses in a second heat exchanger and is pumped back to the evaporator. The heat is removed from the condenser by circulating water from the heat sink. The heat exchangers in the closed cycle are almost always surface condensers (ie. shell and tube, plate-fin, etc.) It has been found that direct contact between the water and secondary working fluid leads to large losses of the working fluid and other problems (Ref.5). In the open cycle, the warm water enters a flash chamber where the pressure is slightly below the saturation pressure. A relatively small portion of the water flash evaporates into steam (~ 0.5% by mass in an OTEC system). This vapor is passed through a low temperature steam turbine that drives a generator. Condensation may take place in a surface heat exchanger as in the closed cycle (producing nearly pure water condensate) or by direct contact with the cooling water.

Another open cycle which is being considered is termed the "lift" cycle. In one application of the lift cycle, warm water is passed through a hydraulic turbine which converts gravity head to electricity. The water is then raised back to its original height by injecting the seawater into a lift tube where the pressure is less than saturation. Steam is produced and the acceleration of the expanding steam drags the unevaporated water up the tube as a mist, much like a "negative" rain storm. The low pressure in the tube is maintained by condensing the steam at the top of the tube. Efficiency, cost, and remaining technological uncertainties are factors in selecting any of these power cycles.

Efficiencies

The Carnot efficiency of these low temperature power cycles can be quite small. With typical OTEC temperatures of 25^{o}C warm water and 5^{o}C cold water first law efficiency is only about 7%. When irreversibilities and power requirements of pumps etc. are considered this value may be reduced to 2-3%. However, since the heat is essentially free, this is a misleading figure of merit. Instead, a second law analysis in which the maximum actual work divided by the maximum available work or exergy may be used. Theoretical second law efficiencies have been derived for both types of Rankine cycles and the lift cycle (Ref.6). Multi-stage Rankine cycles where the warm and cold seawater are used in more than one heat exchanger were also considered. Table 1 compares these various second law efficiencies for the cycles.

Staging greatly increases the efficiency of both Rankine cycles, but capital costs go up as well. One result of a recent study of open cycle OTEC performed by the Florida Solar Energy Center (FSEC) and Creare R&D Inc. showed that in the final analysis, a 2 stage plant produced electricity at only a slightly lower cost than a single stage plant

Table 1. Comparison of the Second Law Efficiencies of Various Power Cycles

Cycle	Second Law Efficiency
3 Stage open Rankine	0.75
2 Stage open Rankine	0.66
Mist Lift	0.59
Open Rankine	0.50
3 Stage closed Rankine	0.48
2 Stage closed Rankine	0.43
Closed Rankine	0.32

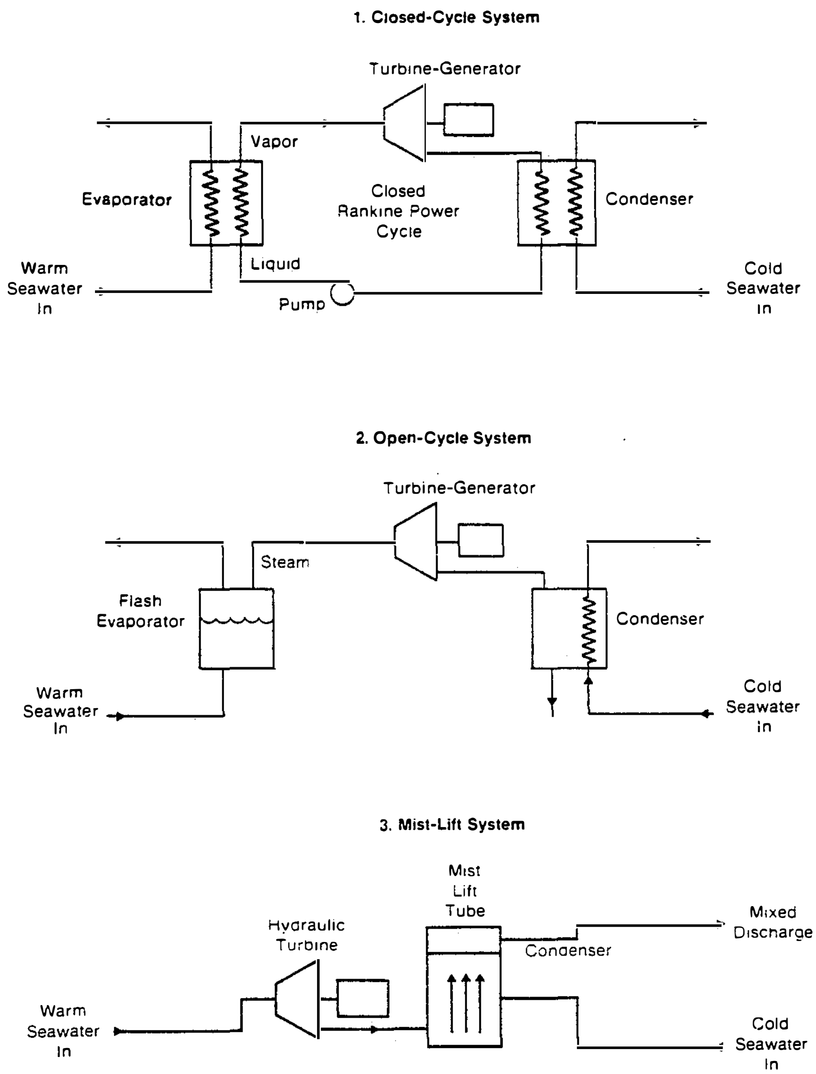

Figure 1. Schematic of the Closed, Open, and Mist-Lift Power Systems

(Ref.7). It should be noted that the ranking of the cycles on an second law efficiency basis is inversely proportional to the technical confidence that currently exists in the open literature for these options.

Comparison of Technologies

The three cycles, mist lift, closed Rankine, and open Rankine are in various stages of development. Table 2 contains various advantages and disadvantages of each of the cycles along with areas of technological uncertainty.

The detailed design and construction of closed Rankine power cycles using organic and other secondary fluids such as ammonia may be completed without major difficulty. Remaining technological problems are related to heat exchanger material compatibility with the working fluid and heat source and sink. For example, seawater and some geothermal fluids are quite corrosive. Seawater may also cause biofouling problems although recent investigations by Argonne National Laboratories (Ref.8) has reduced this concern by conducting tests at the Natural Energy Laboratory (NELH) in Hawaii. Since one of the major cost items in a closed cycle power

Table 2. Comparison of Cycles

	Closed Cycle	Open Cycle	Mist Lift
Working fluid	Ammonia, Freon, organics	Water-heat source	Water-heat source
Evaporator	Large surface type	Direct contact (spout, spray)	Direct contact mist injector
	Moderate heat transfer rates	Large heat transfer rates	Further study required
	Costly metals may be required for corrosion	Inexpensive (plastic)	Inexpensive materials expected
	Large HT area, up to 35% of plant cost	Significant vacuum area required	Lift volume to evaporator plan-form area large
Turbine	Standard equipment or minor modification	Moderate to major development required	Standard equipment
	High pressure vapor, small diameter	Low pressure steam, large diameter	Hydraulic
Condenser	Similar to condenser	Direct contact or surface, hybrid possible	Direct contact
		Inexpensive pipe, nozzle or packed column	Inexpensive pipe, nozzle or packed column
		Potable water by-product possible	
		Noncondensable gas effects	Noncondensable gas effects
Vent compression system	Small, only required due to charging impurities	Continuous non-condensable evolution from direct contact exchangers	Same as open cycle
		Significant power required	
		Standard equipment	

system is the heat exchangers, low cost materials and methods of heat transfer enhancement to reduce heat exchanger size are receiving attention.

Several examples of closed cycle designs are as follows. In 1979 50 kW of gross power was produced in the project called mini-OTEC on a barge off the coast of Hawaii (Ref. 9). A 40 MWe net power plant design has recently been completed as a cost shared venture with DOE and a private group is currently pursuing financing for the project (Ref.10). Recent results for a closed cycle power plant bottoming design on Taipei are discussed in Ref.11.

Several conceptual designs of low temperature open cycle power systems have been completed (Ref.7,11) and Georges Claude built, operated and patented an open cycle OTEC plant in the early 1930's (Ref.12,13) but several issues remain to be fully addressed. For warm water temperatures less than 100°C, the entire power cycle operates under vacuum. Dissolved noncondensable gases may desorb from the warm water in the evaporator and from the cooling water if a direct contact condenser is used. These gases and air leaking into the chambers must be continually removed from the condenser by vent compressors in order to maintain vacuum. The actual amount of gas release is in question and has an impact on parasitic power and compressor sizing. In addition, the affect of the gases on the performance of various heat exchanger geometries is not fully understood. The amount of noncondensable gas may be an order of magnitude higher than in conventional steam power plants.

Since the steam density is low, the turbines required for power extraction in some open cycle designs can be quite large. The maximum existing steam turbines are around 4-5 m in diameter. If a single turbine is used, a 50 MWe gross OTEC plant may require a diameter of around 35 m (Ref.14). In 1980 Westinghouse completed a conceptual design of a 45 m turbine using blades similar to composite helicopter rotors (Ref.15) but the design is unproven. The current attitude is to utilize present blade technology and use modular power units for large capacity plants. Corrosion caused by impurities entrained in the steam during the flash evaporation process and blade erosion may also be a problem.

The pressures differences associated with both Rankine cycles are small (~ 2000 Pa for open Rankine OTEC) therefore, system integration and steam process path design is of critical importance.

The noncondensable gas and condenser issues associated with the open Rankine cycle are common to the mist lift cycle as well. Experiments to examine OTEC applications of the lift cycle have been performed using seawater at NELH using a 4 m high column. Theoretical calculations using results from this column predict a lift height of around 10 m for a $10^{\circ}C$ temperature difference and up to 86 m for a $19^{\circ}C$ temperature difference (Ref.16). Larger heights are possible and must be demonstrated at a scale which can be used to extrapolate to modular sizes.

The power required to operate the plant is significant for most low temperature power cycle designs. With the small driving force for heat exchange, large amounts of water must be circulated. Unless the warm and cold sources are located in close proximity, pumping power to overcome head losses in the water circulation systems may consume a large fraction of the power produced by the generator. With simplistic or poor design approaches it is easy to show how the power to run the pumps and other equipment can exceed the power produced by the generator.

OPEN RANKINE CYCLE OTEC

It is useful to examine actual design parameters for a particular low temperature cycle design. Ocean Thermal Energy Conversion represents the extreme as far as low temperature differences with a typical available temperature drop of $20^{\circ}C$. In addition, the cold seawater must be pumped from ocean depths of around 1000 m. Table 3 shows operating and design parameters plus estimated equipment costs for a 10 MWe net open cycle plant.

An integrated systems analysis code (Ref.14,17) was used to generate these results. Conservative assumptions such as 100% dissolved gas release in the heat exchangers, large detrimental effects of the noncondensables on heat exchanger performance, and relatively small allowable turbine diameters. Projected advances in areas currently under study such as gas deaeration chambers, optimized direct contact condensers, and turbine materials and design advances leading to larger diameters reduce the projected cost of a 10 MWe net plant by nearly 50%.

All OTEC technologies have remaining issues related to the use of seawater, for example, environmental impacts of the temperature, density, and nutrient content of the plant outflow must be fully evaluated. However, by far the largest remaining common questions are related to the seawater supply pipes. For floating plants, vertical suspended pipe technology has been demonstrated (Ref.18), but drag due to currents and vertical wave motions for large diameter pipes is still in question. For land based plants, the design of pipe systems through the surf zone is critical. In addition, mounting pipes on undersea steep slopes presents a large engineering challenge. The cost of these piping systems is also not well defined and piping costs have a large impact on plant design. Cheaper pipes imply that larger diameters may be used to reduce pumping power requirements and that more cold water may be used in the condenser.

CONCLUSION

Low temperature differences can be utilized to generate significant amounts of electricity and to reduce thermal pollution. Several contending power cycles are available and the state-of-the-art for these technologies is in various states of development. Ocean thermal energy conversion is one of the attractive options of this low temperature technology and design parameters for a particular plant have been presented. Open Rankine cycle OTEC is especially attractive due to high efficiency and the possible by-product of fresh water (which is in demand in many areas where a significant OTEC resource exists). Research into areas which have the potential of improving performance and significantly reducing costs of OTEC systems is continuing with the funding of the DOE. The advancements achieved through these programs can readily be transferred to other low temperature applications.

Table 3. Conservative Open Rankine OTEC Plan Parameters

Fluid Flows		
Warm seawater	71,800	kg/s
Cold seawater	33,700	kg/s
Steam	335	kg/s
Noncondensable gas		
from warm seawater	1.26	kg/s
from cold seawater	0.74	kg/s
leakage	0.18	kg/s
Temperatures		
Warm seawater		
inlet	25.0	°C
outlet	22.1	°C
Cold seawater		
inlet	5.0	°C
outlet	11.0	°C
Steam		
evaporator	21.5	°C
condenser	13.5	°C
Component Sizes		
Seawater pipes		
Warm		
length	315	m
diameter	7.72	m
Cold		
length	2235	m
diameter	5.79	m
Discharge		
length	615	m
diameter	7.25	m
Evaporator		
spouts		
number	2800	
height	0.5	m
diameter	0.127	m
area	1175	m^2
Condenser		
Cocurrent stage		
area	510	m^2
height	2.3	m
NTU	1.43	
Countercurrent stage (with packing)		
area	41	m^2
height	3.9	m
NTU	2.42	
Exhaust compression		
Number of stages	6	
stage compression ratio	2.21	
1^{st} stage volumetric flow	1100	m^3/s
Turbine/generator		
number (double-sided)	12	-
diameter	4.52	m
Power		
Turbine-generator	16,600	kW
Exhaust compressors	3,340	kW
Warm seawater pumping	980	kW
Cold seawater pumping	1,360	kW
Discharge pumping	830	kW
Net delivery	10,090	kW
Estimated Component Cost		
Turbine-generator	32,650	$1000
Evaporator/mist removal	4,700	$1000
Condenser	440	$1000
Heat exchanger platform area	12,240	$1000
Exhaust compression system	9,280	$1000
Pumps	4,750	$1000
Seawater pipes	37,490	$1000
Total	101,550	$1000

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