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# Theoretical Analysis of Closed Rankine Cycle Solar Pond Power Generator

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**Abstract**

Thermal energy extraction from solar pond is theoretically studied with the use of Rankine cycle heat engine. The Rankine power cycle configuration consists of evaporator, turbine, condenser, feed pump and R-134a which is used as the working fluid. A solar pond is considered as the heat source for the evaporator. Fresh water circulates through an internal heat exchanger, located in the lower convective zone of the pond, and transfers its thermal energy to evaporator. The heat that is absorbed increases the temperature of a working fluid and causes the working fluid to vaporize. When the working fluid has taken enough potential energy, the fluid vaporizes and begins to rise, thereby converting some of the potential energy to kinetic energy. The vapor flows under high pressure to the turbine and thereby expanding through the turbine from a higher pressure to a lower pressure. Useful work can be extracted from this expansion process. The turbine is placed in between the evaporator and condenser section of the cycle. The water is acting as heat sink for the condenser. An attempt is made to analyze the thermodynamic aspects of the cycle and the net works generated by the system are elaborated. The report presents the analysis of an alternative method of thermal energy extraction from solar energy thermal resource with the use of solar pond.

**Keywords:** Solar Pond, Refrigerant, Rankine cycle and Thermal Energy Extraction

## 1. Introduction

To meet the increasing world demand for energy, the use of fossil fuel to produce power has become wide spread. Unfortunately fossil fuels are non renewable energy sources, and they pollute the environment and are considered as the largest source of emissions of carbon dioxide, which is largely blamed for the global warming and climate changes. This trend can be reduced by the construction of power plants using renewable energy sources (Zekai, 2004). There are many forms of renewable energy sources available, and this paper will focus on thermal energy extraction from solar pond that is theoretically studied with the use of Rankine cycle heat engine.

A solar pond is simply a pool of water which collects and stores solar energy. It contains layers of salt solutions with increasing concentration (and therefore density) to a certain depth, below which the solution has a uniform high salt concentration. When solar radiation (sunlight) is absorbed, the density gradient prevents heat in the lower layers from moving upwards by convection and leaving the pond. This means that the temperature at the bottom of the pond will rise to over 90 °C while the temperature at the top of the pond is usually around 30 °C. The heat trapped in the salty bottom layer can be used for many different purposes, such as the heating of buildings or industrial hot water or to drive a turbine for generating electricity (Wikipedia, 2007).

There are many advantages of using solar based power plants (Wu, 1998), and a few benefits are noted such as, heat energy is provided without burning fuel thus reducing pollution, conventional energy resources are conserved, there are no costs associated with fuel, the low operating temperatures and pressure reduces the component costs and it has a 24 hour a day potential. The report presents the theoretical analysis of an attractive method of thermal energy extraction from solar pond that is theoretically studied with the use of Rankine cycle heat engine.

## 2. Rankine cycle solar pond power generator

A solar thermal energy extraction from solar pond closed power cycle is schematically shown in figure1. In this system heat is transferred from solar pond to the working fluids refrigerant in an evaporator. The heat transfer mechanism that drives a closed Rankine power cycle is the recirculation of a working fluid through a cycle of evaporation, vapor transfer, condensation, and liquid return (Akbarzadeh, 2001). Fresh water circulates through an internal heat exchanger, located in the lower convective zone of the pond, and transfers its thermal energy to evaporator. The power cycle gets the energy from absorbing the heat from the solar pond. The heat that is absorbed increases the temperature of a working fluid inside of the evaporator tubes and causes the working fluid to evaporate at an elevated pressure (Rai, 2002).

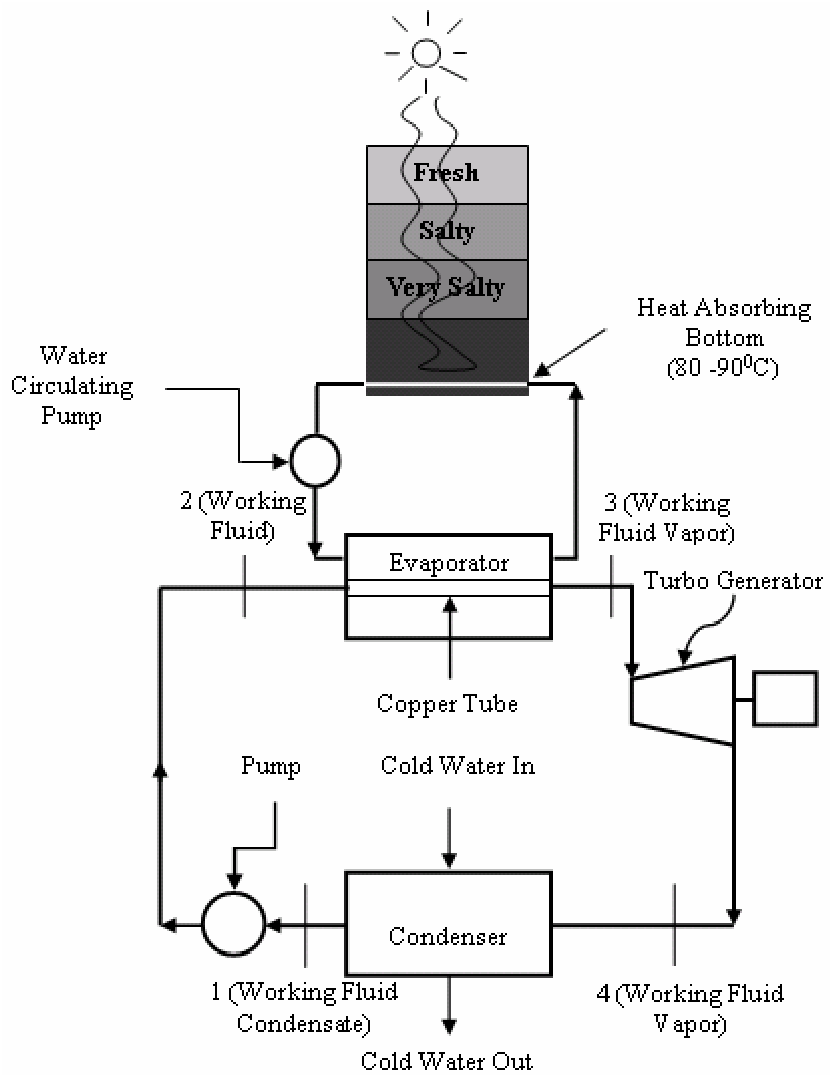


Figure 1. Schematic diagram of Rankine cycle solar pond power generator

The less dense vapor then rises. As the vapor is rising, it is expanding from a higher pressure to a lower pressure. Useful work can be extracted from this expansion process. As the working fluid flows from the evaporator to the condenser in the vapor phase, the kinetic energy of the working fluid is increased (Patrick, 1998). When a turbine and generator are incorporated into the high velocity vapor stream, electric power can be extracted. When the vapor passes through the turbine it loses the kinetic energy and the pressure and temperature of the vapor decreases. The vapor at state 4 is then sent to the second heat exchanger (condenser) where heat is transferred from the vapor to cold water and thus, the working fluids returns to a saturated liquid at state 2 back to the first heat exchanger where the process is repeated (Wu, 1198).

**3. Solar pond as a heat source for the Rankine cycle solar pond power generator**

Solar ponds present an economical way to obtain large amounts of low grade heat. Solar ponds utilize the natural properties of salt water to collect and store the heat energy. The most common type of solar pond is the salt gradient pond, which has the three different layers of salt concentration. Sunlight passes through the water with the majority of the sun light being absorbed by lower salt layers of water and the heat absorbing lining (Mehmet, 2006). This heats the lower layers of the pond. The concentrations of the salt layers are created such that the bottom layer of very salty water is denser than the second layer, even when heated to near boiling temperatures. Likewise, the middle layer of salty water is designed to be denser than the fresh water on top. This inhibits the convection of heat throughout the pond. The heat is extracted from the bottom layer of the pond, which is the saltiest and reaches the highest temperatures ( Rai, 2002).

**4. Selection of heat source and heat sink**

A reasonable temperature for a solar pond is to reach heat up to 90$^0$C. A reasonable temperature for the ambient temperature of the air is 20$^0$C. For this reason, a heat sink temperature of 20$^0$C is assumed. Since not all the heat would be transferred from the heat sink and heat source to the Rankine cycle, the assumed evaporator temperature in the cycle is 80$^o$C and the condenser temperature of our Rankine cycle is 22$^0$C.

**5. Working fluid for the Rankine cycle solar pond power generator**

The working fluid for a phase-change cycle like the one found in a Rankine cycle power plant has the following desirable characteristics. Critical temperature well above the highest temperature that can be used in the cycle. This makes it possible to vaporize the working fluid and thus adds a considerable amount of heat to it at the maximum temperature. Neither very high nor very low saturation pressures at the maximum and minimum temperatures of the cycle (Ganic, 1980 & Johnson, 1983). In this investigation, R-134a is used as working fluid because of its superior high thermal efficiency, conductivity and ozone-friendly nature.

**6. Analysis of closed Rankine cycle solar pond power generator**

The system analyzed here is a 10 kW power plant, which assumes warm water entering temperature of 85$^0$C and exiting temperature of 75$^0$C, cold water entering temperature of 20$^0$C and exiting temperature of 24$^0$C, the specific state points 1, 2, 3 and 4 at temperatures of 22$^0$C, 22$^0$C, 80$^0$C and 80$^0$C, respectively. Also temperature differences across both heat exchangers are modeled as isobaric (both hot and cold side). In addition, the two heat exchangers are assumed to have an overall coefficient (U) of 1 kW/m$^2$K [2].

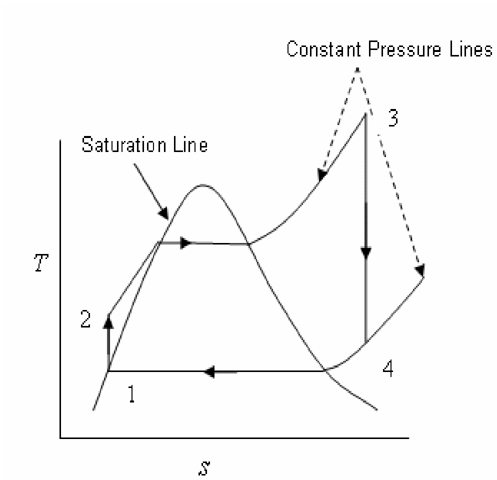


Figure 2. Ideal Rankine cycle on a temperature entropy diagram

The cycle is assumed to be an idealized Rankine cycle. The figure 2 shows the different steps of the Rankine cycle according to Nguyen et al. (Nguyen, 1994). The first process (From 1-2) consists of adiabatic compression of the liquid. During the second process (From 2-3) heat is added isobarically to convert the liquid to a vapor. The third process (From 3-4) consists of adiabatic expansion of the vapor to lower pressure. During the fourth process (From 4-1) there is isobaric heat rejection that condenses the vapor back to a liquid. The above four processes are repeated over and over again to produce the Rankine cycle.

Figure 1 shows a simplified flow diagram of the closed cycle plant. Where, h is the enthalpy at the indicated state point. It follows that the heat-added plus the pump-work is equal to the heat-rejected plus the turbine work. From the state point enthalpies, the heat transferred to the working fluid in the boiler, the heat transferred from the working fluid in the condenser, work generated by the turbine, work generated by the pump, net work generated by the heat engine, thermodynamic cycle efficiency, mass flow rate of the refrigerant, boiler and condenser heat transfer rate, mass flow rate of warm and cold water, boiler and condenser surface area and specific power output of the closed Rankine cycle plant can be calculated from the equations (1) to (17) as follows (Wu, 1998).

**State 1-2**

Reversible adiabatic pumping process in the pump

Pump work (kJ/kg) $$W_{pump} = V_1(P_2 - P_1) \quad (1)$$

$$W_{pump} = 0.336 \text{ kJ/kg}$$

$$W_{pump} = h_2 - h_1 \tag{2}$$
$$h_2 = 230.336 \text{ kJ/kg}$$

**State 2-3**

Heat supplied from evaporator at constant temperature to change state 2 into saturated R-134a at constant pressure.

Heat added (kJ/kg)
$$q_A = h_3 - h_2 \tag{3}$$
$$q_A = 198.864 \text{ kJ/kg}$$

Acknowledging the fact that is a 1 kW power plant, the mass flow rate of the working fluid ($m_R$) can be found via;

$$m_R = \frac{P_{out}}{W_{net}} \tag{4}$$
$$m_R = 0.180 \text{ kg/s}$$

Boiler heat transfer rate (kJ/s)

$$Q_{boil} = m_R(q_A) \tag{5}$$
$$Q_{boil} = 35.795 \text{ kJ/s}$$

Surface area of the boiler ($m^2$)

$$A_{boil} = \frac{Q_{boil}}{\{U_{boil}[(T_{w1} + T_{w2})/2 - (T_2 + T_3)/2\}} \tag{6}$$
$$A_{boil} = 1.234 \text{ m}^2$$

Mass flow rate of warm water (kg/s)

$$m_{warm} = \frac{Q_{boil}}{[Cp_{water}(T_{w1} - T_{W2})]} \tag{7}$$
$$m_{warm} = 0.855 \text{ kg/s}$$

Where

$T_{w1}$ Temperature of the warm water entering the boiler ($85^0$C)

$T_{w2}$ Temperature of the warm water exiting the boiler ($75^0$C)

**State 3-4**

Isentropic expansion of the vapor across the turbine, including partial condensation.

$$x_4 = \frac{s_4 - s_{f@22^oC}}{s_{v@22^oC}} = 0.348 \tag{8}$$

$$h_4 = h_{f@22^oC} + x_4 h_{v@22^oC} \tag{9}$$
$$h_4 = 373.446 \text{ kJ/kg}$$

Turbine work (kJ/kg)
$$W_{turb} = h_3 - h_4 \tag{10}$$
$$W_{turb} = 55.574 \text{ kJ/kg}$$

Cycle Network (kJ/kg)
$$W_{net} = W_{turb} - W_{pump} \tag{11}$$
$$W_{net} = 55.574 \text{ kJ/kg}$$

**State 4-1**

Complete condensation in the condenser at constant temperature.

Heat rejected (kJ/kg)
$$q_R = h_4 - h_1 \tag{12}$$
$$q_R = 143.446 \text{ kJ/kg}$$

Condenser heat transfer rate (kJ/s)

$$Q_{cond} = m_R(q_R) \tag{13}$$
$$Q_{cond} = 25.820 \text{ kJ/kg}$$

Surface area of the Condenser ($m^2$)

$$A_{cond} = \frac{Q_{cond}}{\{U_{boil}[(T_1 + T_4)/2 - (T_{c1} + T_{c2})/2\}} \tag{14}$$

$A_{cond}$ = 0.890 m$^2$

Mass flow rate of cold water (kg/s)

$$m_{cold} = \frac{Q_{cond}}{[Cp_{water}(T_{c2} - T_{C1})]} \tag{15}$$

$m_{cold}$ = 1.539 kg/s

Where

$T_{c1}$ Temperature of the cold ocean water entering the condenser (20$^0$C)

$T_{c2}$ Temperature of the cold ocean water exiting the condenser (24$^0$C)

Thermal Efficiency (%)

$$\eta_{thermal} = \frac{W_{net}}{q_A} = \frac{[h_3 - h_4] - [h_2 - h_1]}{[h_3 - h_2]} \tag{16}$$

$\eta_{thermal}$ = 27.94 %

The final calculation is that of the Specific power (*P*). It is accomplished by the following equation

$$P = \frac{Q_{boil}}{(A_{boil} + A_{cond})} \tag{17}$$

$P$ = 16.852 kW/m$^2$

## 7. Conclusion

The analysis of thermal energy extraction from solar pond is theoretically studied with the use of closed Rankine cycle solar pond power generator. It has been concluded that the generation of maximum thermal efficiency of 27.94 % and specific power of 16.852 kW/m$^2$ can be achieved by using the effective closed Rankine cycle solar pond power generator. To work out minimal amount of power generation and continuous production of power from solar energy source, a closed Rankine cycle solar power generator system is an extremely attractive option. However other factors such as maintenance, operating cost and transmission, etc, were ignored in this analysis and thus may have significant impact on future power plants design. Further investigations are needed in order to test the sensitivity of the theoretical efficiency gain from solar energy heat extraction before moving to practical applications in these areas.

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**Appendix**

Table 1.Values referred from Refrigerant R-134a table (Balany, 2003).

| Description | Temperature ($^0$C) | Enthalpy( kJ/kg) | Pressure (bar) |
|---|---|---|---|
| State 1 | 22 | 230.210 | 6.0777 |
| State 2 | 22 | 230.336 | 16.000 |
| State 3 | 80 | 429.020 | 16.000 |
| State 4 | 80 | 373.446 | 6.013 |