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PERFORMANCE ANALYSIS OF FLUIDS R12, R152A, R134A AND R500 FOR AN ORGANIC RANKINE CYCLE USED IN AN OTEC POWER PLANT

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Abstract. Ocean Thermal Energy Conversion (OTEC) is a process that can produce electricity by using the temperature difference between deep cold ocean water and warm tropical surface waters. OTEC plants pump large quantities of deep cold seawater and surface seawater to run a power cycle and produce electricity. OTEC is firm power, a clean energy source, environmentally sustainable and capable of providing massive levels of energy. A performance study of the fluids R12, R152a, R134a and R500 was performed for the production of 100 MW in an organic Rankine cycle (ORC) working in a power plant for ocean thermal energy conversion. The performance of the fluids was evaluated by the ratio between the net power developed by the cycle and the total area of heat transferred from the boiler and condenser. This parameter is called specific power. The specific power is determined through mass and energy balances in the ORC components and by the use of the arithmetic average temperature in boiler and condenser. Fluid properties were obtained using the Engineering Equation Solver (EES) for several boiler and condenser pressures. For each working fluid was obtained the surface graph indicating the optimum system operation point.

Keywords: *organic Rankine cycle, OTEC, optimization, power.*

1. INTRODUCTION

The world energy consumption has increasing each year, as well as, the concern with emission of carbon dioxide. Most of countries use fossil fuel for generation of electricity. In order to attend an increase of energetic demand and to decrease emission of carbon dioxide coming from burning of fossil fuel for generation of electricity, researches has been done in search of renewable sources of energy. Several are renewable sources of energy, however, some factors limit its utilization, like, implantation cost and low efficiency.

In 1881, a French physicist called Jacques Arsene D'Arsonval discovered the concept of ocean thermal energy conversion (OTEC). His student, George Claude, built an experimental open-cycle OTEC plant at Matanzas Bay, Cuba in 1930. This plant produced 22 kW of electricity by using a low-pressure turbine (Gupta and Roy, 2007). This process consists of utilizing the temperature difference between the surface and deepest part of ocean for generation of electricity. The warm water coming from ocean surface is utilized to vaporize the working fluid for that the same can expand in the turbine generating work. The cold water coming from deepest part of ocean is utilized to condense the working fluid. Globally, three concepts of OTEC plant are acquaintance. They are: open-cycle, closed-cycle and hybrid-cycle (Gupta and Roy, 2007).

In tropical and subtropical regions, the temperature difference between warm water from ocean surface and 1000 meters of depths water, exceed generally 20 ºC, that is the minimum difference necessary to produce energy through OTEC plant (Luís, 2010). One OTEC plant is suitable for tropical oceans extending from 20 ºN to 20º S of equator line (Gupta and Roy, 2007). One difficulties of implantation these plants are that due to small temperature difference between warm source and cold source the OTEC installations achieve lowest efficiency in the range from 6 % to 8 % (Masutani and Takahashi, 2001). The low efficiency in the conversion of energy of plant OTEC mean that more of 90 % thermic energy extracted from ocean surface is waste, being reject to cold part of ocean (Masutani and Takahashi, 2001). There are many advantages in the utilization of OTEC plant, as indicate below (Wu and Burke, 1998):

- No pollution;

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- It is a renewable energy source;
- It has a 24 h a day potential;
- It produces fresh water;
- The produced water can be used to cultivate aquaculture products;
- The cold seawater can be used to air conditioning after OTEC use;
- There are no costs associated with fuel;
- The low operating temperatures and pressures reduce component costs.

The OTEC plants, normally, using the organic Rankine cycle (ORC) in its operations, representing betters efficiency than conventional Rankine cycle operating between the same temperature differences. The organic Rankine cycle differences of conventional Rankine cycle for utilization of working fluid. While in the conventional Rankine cycle utilize organic fluids that require of one less quantity of heat to vaporize, being in this way can utilize heat source of median temperature. The saturation curve is one very important characteristic of working fluids at an ORC, being this characteristic affect the applicability of fluid and cycle efficiency (Hung, *et al*., 1997).

The working fluids suitable for utilization at an organic Rankine cycle can be classified in three groups, according to the entropy-temperature diagram (Kosmadakis, *et al*., 2009):

- Dry fluids, in general high molecular weight, such as R113;
- Wet fluids, in general low molecular weight, such as water;
- Isentropic fluids, possess a saturated vapor curve almost vertical, such as R11 and R12.

In the ORC is desirable the use of dry and isentropic fluids, because these fluids have not became saturated after to produce work in the turbine because of an accented drop in its specific enthalpy (Kosmadakis, *et al*., 2009).

Besides, as the most of organic fluids suffer chemical decomposition and temperature high and pressures, an ORC system must operate very below of temperature and pressure which the fluids are chemically unstable (Hung, *et al*., 1997). The present paper has objective to analyze the performance of fluids R12, R152a, R134A and R500 for an ORC utilized at an OTEC plant for production of 100 MW.

In this work, the performance of each fluid is evaluated through a relation between net power developed from cycle and total area of heat exchange of boiler and condenser. This parameter is called specific power and was proposed to Wu and Burke, 1998. For each one of the four fluids will be determined the best point of operation of cycle in function of boiler and condenser operation pressures, in others words, the point of maximum specific power. The organic Rankine cycle is analyzed in steady state, with variation of kinetics and potential energy despise. The turbine and the pump are considered adiabatic with isentropic efficiency acquaintance. The flow in the boiler and condenser are considered without pressure drop.

2. MATHEMATICAL MODEL

A schematic ORC operating in an OTEC plant is shown in Fig. 1. This power plant closed, heat is transferred from the warm water of the ocean surface $T_{W,i}$ to the working fluid in a heat exchanger (boiler). Due to the low boiling point of organic fluids, it is assumed that the working fluid becomes a saturated vapor ($x_3 = 1$) at state 3 and expands into a turbine coupled to an electric generator to produce electricity. The steam at state 4 is sent to a second heat exchanger (condenser) where heat is transferred from the vapor to the cold water from the ocean bed $T_{C,i}$, and then the working fluid returns as a saturated liquid ($x_1 = 0$) at state 1. The liquid is finally pumped to the state 2 and the process is repeated.

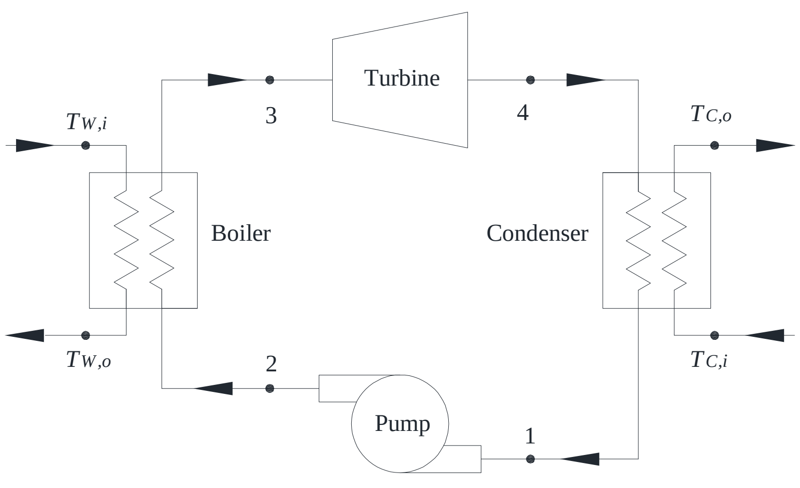

Figure 1. Scheme of a closed cycle of an OTEC plant.

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For analysis of OTEC plant to produce 100 MW, some considerations were made. It is assumed that the isentropic efficiency of the turbine and pump are equal to 90%. The condenser and the boiler are modeled as isobaric. The temperature of the ocean surface (warm part) at the input $T_{W,i}$ and output $T_{W,o}$ boiler are, respectively, 28 º C and 24 º C. The temperature of the cold part of the ocean at the input $T_{C,i}$ and the output $T_{C,o}$ of the condenser are respectively 4 ° C and 8 °C. It is considered that the overall heat transfer coefficient in the boiler U_W and condenser U_C are equal to 1000 $W/m^2.K$.

To analyze the performance of the working fluid in the OTEC plant was used the ESS software, with the advantage of having the thermodynamic properties of the working fluid and still able to perform mathematical routines. The variables selected to be analyzed in the EES are boiler pressure P_{boil} and condenser pressure P_{cond}. Through combining various pressures of the boiler and condenser, then obtained the specific power P_e for each working fluid. The mathematical model for this purpose is based on the first law of thermodynamics to open systems operating in steady state, with variations of kinetic and potential energy negligible.

The mass flow of the working fluid cycle may be calculated as:

$$\dot{m} = \frac{\dot{W}_{cycle}}{h_3 - h_4 - (h_2 - h_1)} \tag{1}$$

where h_3 is the specific enthalpy from the saturated steam in stage 3 and h_1 is the specific enthalpy from the saturated liquid at state 1. The rate of heat transference which enters in the cycle per unit of mass flow of the working fluid can be calculated by combination the mass and energy balance at the boiler:

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_3 - h_2 \tag{2}$$

The rate of heat transfer which leaves the cycle per unit of mass flow of the working fluid can be calculated by the combination of the mass and energy balance in the condenser:

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_4 - h_1 \tag{3}$$

The power developed by the turbine per unit of mass flow of the working fluid can be calculated by the combination of the mass and energy balance in the turbine:

$$\frac{\dot{W}_t}{\dot{m}} = h_3 - h_4 \tag{4}$$

The power consumed by the pump per unit of mass flow of the working fluid can be calculated by the combination of the mass and energy balance at the pump:

$$\frac{\dot{W}_p}{\dot{m}} = h_2 - h_l \tag{5}$$

The net power developed by the cycle per unit of mass flow rate of the working fluid can be calculated as:

$$\frac{\dot{W}_{net}}{\dot{m}} = \frac{\dot{W}_t}{\dot{m}} - \frac{\dot{W}_p}{\dot{m}} \tag{6}$$

The thermal efficiency of the cycle η is defined as:

$$\eta = \frac{\dot{W}_{net}/\dot{m}}{\dot{Q}_{in}/\dot{m}} \tag{7}$$

The heat transference rate which enters the cycle can be calculated using the Eqs. (2) and (1), in others words:

$$\dot{Q}_{in} = \dot{m}\frac{\dot{Q}_{in}}{\dot{m}} \tag{8}$$

The heat transference rate which leaves the cycle can be calculated using the Eqs. (3) and (1), in others words:

$$\dot{Q}_{out} = \dot{m}\frac{\dot{Q}_{out}}{\dot{m}} \tag{9}$$

The mass flow of water in the warm part of the ocean can be calculated by means from the combination of mass and energy balances in the boiler, in others words:

$$\dot{m}_{W,w} = \frac{\dot{Q}_{in}}{c_{p,W}(T_{W,i} - T_{W,o})} \tag{10}$$

where $c_{p,W}$ is the specific heat at constant pressure of water in the warm part of the ocean.

The mass flow of water in the cold part of the ocean can be calculated by means from the combination of mass and energy balances on the condenser, in others words:

$$\dot{m}_{W,c} = \frac{\dot{Q}_{out}}{c_{p,C}(T_{C,o} - T_{C,i})} \tag{11}$$

where $c_{p,C}$ is the specific heat at constant pressure of water in the cold part of the ocean.

The area of heat exchange in the boiler can be calculated by an expression similar to the law of cooling Newton for convection using the arithmetic average temperature for each of the fluids, in others words:

$$A_{boil} = \frac{\dot{Q}_{in}}{U_W\left[\frac{T_{W,i} + T_{W,o}}{2} - \left(\frac{T_2 + T_3}{2}\right)\right]} \tag{12}$$

In a similar way, the area of heat exchange in the condenser can also be calculated by an expression similar to the law of cooling Newton for convection using the arithmetic average temperature for each of the fluids, in others words:

$$A_{cond} = \frac{\dot{Q}_{out}}{U_C\left[\frac{T_1 + T_4}{2} - \left(\frac{T_{C,i} + T_{C,o}}{2}\right)\right]} \tag{13}$$

Finally, the specific power to the OTEC power cycle is defined as:

$$P_e = \frac{\dot{W}_{cycle}}{A_{boil} + A_{cond}} \tag{14}$$

The isentropic efficiency from the turbine is calculated as:

$$\eta_t = \frac{h_3 - h_4}{h_3 - h_{4s}} \tag{15}$$

The isentropic efficiency from the pump is calculated as:

$$\eta_p = \frac{h_2 - h_1}{h_{2s} - h_1} \tag{16}$$

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3. RESULTS

After the implementation of the mathematical model for each working fluid in the ESS to the considerations mentioned previously, it was the change in pressure in the boiler and condenser in order to obtain maximum specific power output from the OTEC plant for each working fluid. The boiler pressure oscillated between 500 kPa to 700 kPa at intervals of 10 kPa and the condenser pressure oscillated from 390 kPa to 590 kPa also at intervals of 10 kPa. Using the obtained results, was generated a table with the values of specific power for each pair of pressures. In order to facilitate the visualization of the results obtained, the data were exported to Excel to obtain a surface graph. Thus, were obtained four graphs relating the boiler pressure, the condenser pressure and the specific power.

The Fig. (2) represents the surface graph for the working fluid R-12. To the conditions imposed, the maximum specific power output was 137,8 W/m^2 with the operating pressure system of 700 kPa in the boiler and 440 kPa in the condenser.

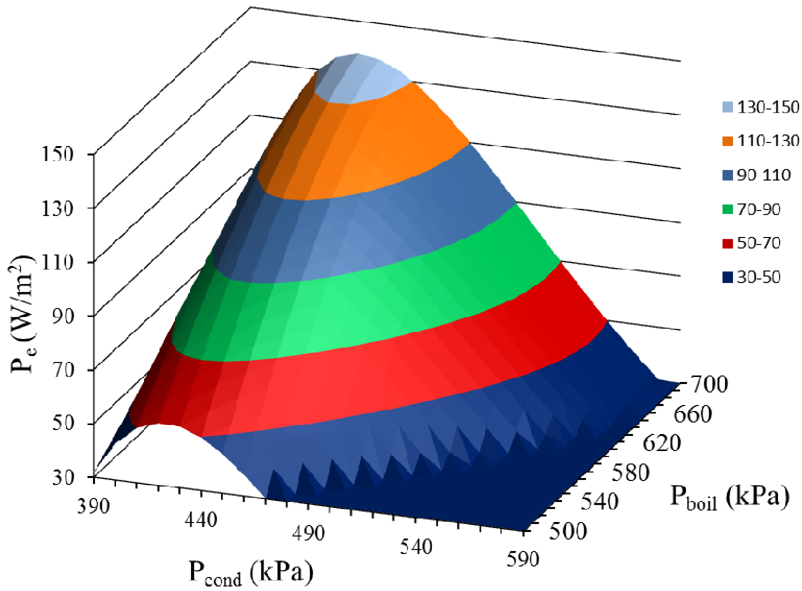

Figure 2. Behavior of specific power for the working fluid R-12.

The Fig. (3) represents the surface graph for the working fluid R-134a. For the conditions imposed, the maximum specific power output was 134,1 W/m^2 with the operating pressure system of 700 kPa in the boiler and 440 kPa in the condenser.

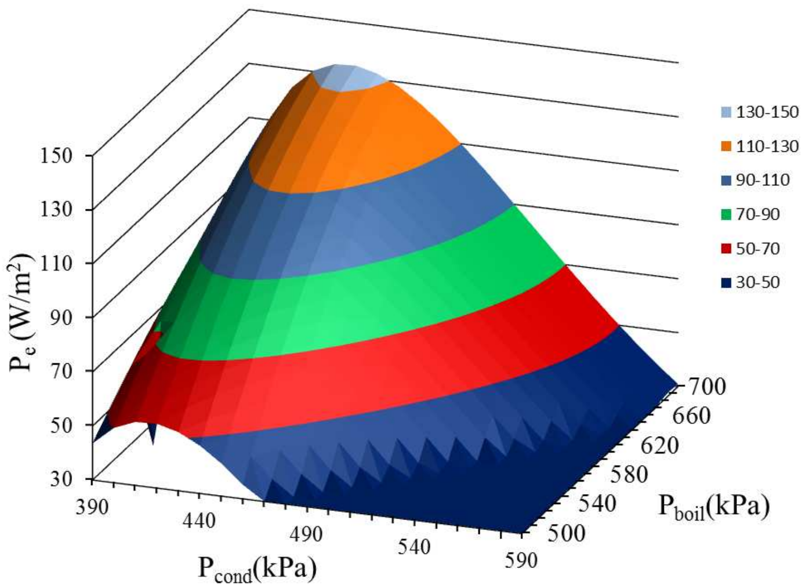

Figure 3. Behavior of specific power for the working fluid R134a.

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The Fig.(4) represents the surface graph for the working fluid R-152a. For the conditions imposed, the maximum specific power output was 142,2 W/m^2 with the operating pressure system of 690 kPa in the boiler and 390 kPa in the condenser.

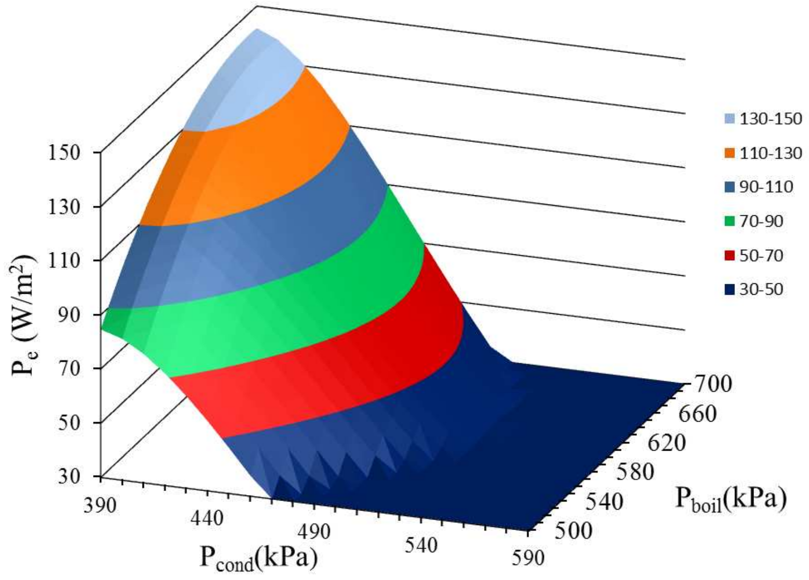

Figure 4. Behavior of specific power for the working fluid R152a.

Finally, the Fig. (5) represents the surface graph for the working fluid R-500. For the conditions imposed, the maximum specific power output was 105,3 W/m^2 with the operating pressure system of 700 kPa in the boiler and 520 kPa in the condenser.

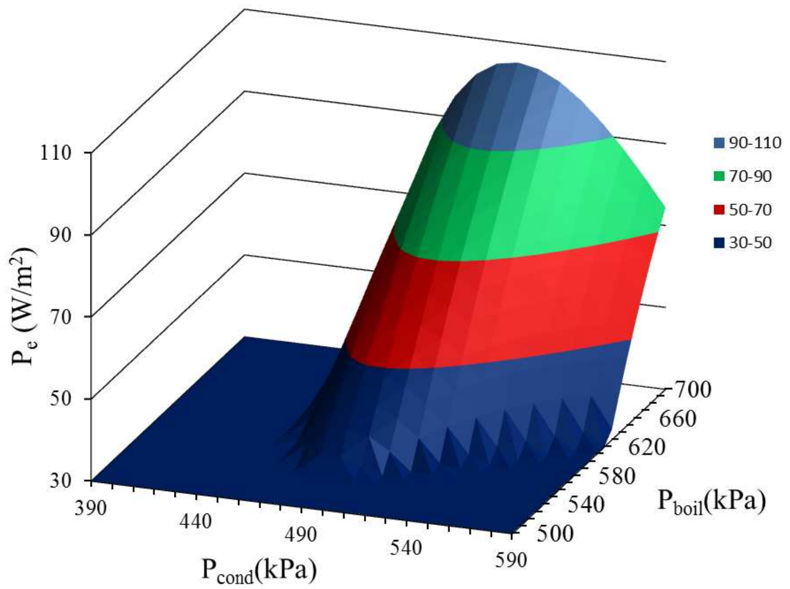

Figure 5. Behavior of specific power for the working fluid R500.

4. CONCLUSIONS

The power plants using temperature differences between the ocean's layers, called OTEC'S, are in full development, being a promising technique for future energy sources. The results obtained here showed that there is a specific combination of pressures of the boiler and the condenser, which maximizes the specific power of the plant, defined as the ratio between the net power developed by the cycle and the total area of heat transference of the boiler and the condenser. Having as objective the function specific power, being an analysis of performance of R-12, R-134a, R-152a and R-500 fluids, used as working fluid in power plants. The higher specific power is 142,2 W/m^2, obtained from the

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working fluid R-152a with the operating pressure system of 690 kPa in the boiler and 390 kPa in the condenser. The lower specific power is 105,3 W/m^2, obtained from the working fluid R-500 with the operating pressure system of 700 kPa in the boiler and 520 kPa in the condenser. However, other factors such as thermal efficiency and cost of operation and maintenance were ignored in this work and can have a significant impact on future projects of OTEC power plants.

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6. RESPONSIBILITY NOTICE

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