Journal of Mechanics Engineering and Automation 8 (2018) 309-315
doi: 10.17265/2159-5275/2018.07.004

Thermal Comparison of an Organic Rankine Cycle Activated by a Low-Temperature Geothermal Heat Source

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Abstract: This study compares the results from the thermodynamic analysis at an Organic Rankine Cycle power plant, for first and second law efficiency, operating with 14 different working fluids. This plant—located in the town of Los Negritos, in the municipality of Villamar, in the State of Michoacán, Mexico—uses heat from a low-temperature geothermal source with the purpose of identifying the working fluids that are best suited for the operating conditions at hand. REFPROP v.8.0 software was used to collect the thermodynamic properties. Of all the thermodynamic parameters that were analyzed, the fluid that performed the best had an overall energy efficiency of 5.87%, an overall exergy efficiency of 43.07%, and a net output power of 13.04 kWe.

Key words: Organic Rankine cycle, geothermal energy, Los Negritos, thermodynamic analysis, exergy.

Nomenclature

WF	Working fluid
GF	Geothermal fluid
ht	High-temperature of geothermal source (℃)
lt	Low-temperature of geothermal source (℃)
ST	Steam turbine
CON	Condenser
EG	Electric generator
SG	Steam generator or evaporator
P	Pump
kWe	Electric kilowatts
kWt	Thermal kilowatts
ORC	Organic Rankine cycle
$\dot{W}$	Power (kW)
$\dot{Q}$	Heat (kW)
$\dot{E}x$	Energy (kW)
$\dot{m}$	Mass flow rate (kg/s)
h	Enthalpy (kJ/kg)
s	Entropy (kJ/kg K)
R	Relationship of mass flow rates
$\dot{E}$	Energy (kW)
η	Efficiency
P	Pressure (kPa)
T	Absolute temperature (K)

Subscripts

A	Used
C	Passed
D	Destroyed
in	Input
out	Output
i	Number of the fluids in the system
th	Thermal
Ex	Exergy
a	Input geothermal fluid
b	Output geothermal fluid
0	Environmental state of reference

Corresponding author: Iván Vera Romero, M.Sc., research fields: energy saving, simulation of thermal processes.

1. Introduction

The growing demand for energy worldwide calls for new and increasingly improved technological proposals for its use that perform better, which helps increase the supply and decrease the harmful impact on the environment of the products or byproducts produced during the production and transformation processes. With demographic growth and the demand for services, the increase in countries' installed generating capacity along with their electricity generation is essential for guaranteeing proper development. The dependence on fossil fuels that has existed and continues to exist to satisfy these needs [1] has had repercussions on the generation and accumulation of Greenhouse Gases (GHG) in the atmosphere, which causes different environmental problems [2].

Geothermal energy is a primary energy source that has proven to be a clean source for generating electricity; it has high potential for being exploited and a low impact on the environment [3]. As a country, Mexico has high potential for this resource [4, 5], positioned among the top five countries with the greatest exploitation worldwide (Table 1). With a total net capacity of 932 kWe (www.cemiegeo.org), it is distributed as shown in the following (Table 2).

The state of Michoacán is situated on a geological fault line, named the Trans-Mexican Volcanic Belt (Fig. 1) [6], where the Los Azufres geothermal field is located [7, 8]. Places such as Ixtlan de Los Hervores, Los Negritos, and Pajacuaran, which are found along this same fault line, have easily detectable thermal manifestations [9-11].

This resource has mainly been used for therapeutic purposes and tourism. In the Los Negritos area, in the municipality of Villamar [12], the manifestation is in plain sight, there are natural occurrences of mud that has considerable energetic content and reaches temperatures that are around the boiling point for water, according to the area's atmospheric pressure (92 °C). This source of low-temperature heat can be used for different purposes, including for therapeutic hot springs, heating, greenhouses, drying wood, and dehydrating fruits. However, generating electricity is a strategic option for the country's development, and therefore, it is the focus of this study.

The temperatures in this area are considered to be in an interval of low temperatures, which prevents them from being used by systems or power cycles with conventional working fluids, such as a steam-operating Rankine cycle. However, systems based on the Organic Rankine Cycle (ORC) can be employed [13], which works with different types of fluids, mainly those with low-boiling points; organic fluids are among those that stand out [14-17]. These types of cycles are generous because they use low-temperature heat sources to carry out mechanical work or produce electrical power, which makes them an ideal option for using the geothermal resources in this area to generate electricity.

ORCs are systems that are mainly composed of the

Table 1 Worldwide gross installed capacity per country.

No.	Country	Net capacity (MWe)
1	United States	3,567
2	Philippines	1,930
3	Indonesia	1,375
4	Mexico	1,069
5	New Zealand	973
6	Italy	944

Table 2 Geothermal fields in operation in Mexico.

Place	State	Installed capacity (MWe)	Operating (GWh/año)
Cerro Prieto	Baja California	570	4,100
Los Azufres	Michoacán	248	1,550
Los Humeros	Puebla	94	340
Las Tres Vírgenes	Baja California Sur	10	55
Domo San Pedro	Nayarit	10	--------------

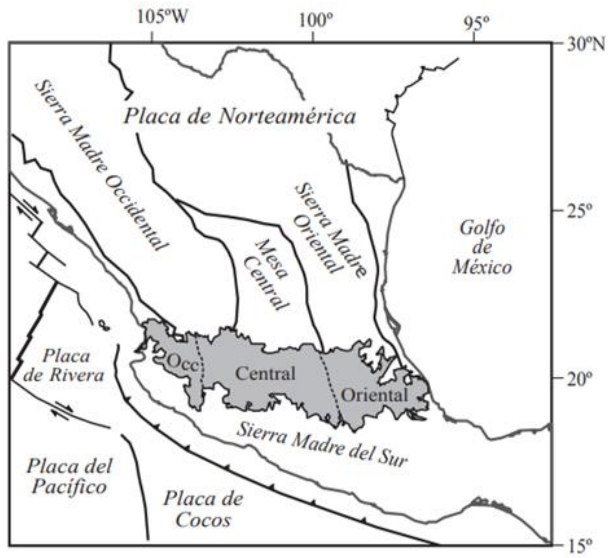

Fig. 1 Trans-Mexican Volcanic Belt Fault Line. Source: [6].

following five machines [18], as in a conventional Rankine cycle (Fig. 2): a steam generator (SG), a turbine (ST), an electric generator (GE), a condenser (CON), and a pump (P). The working fluid recovers heat from the geothermal source in a heat exchanger (SG), taking it to the state of saturated or overheated steam (2-3). This fluid is directed to a steam turbine (ST) with backpressure or condensation, depending on the system's needs (3-4). Then, it is put into a condenser, which will use the fluid to remove the necessary heat and convert it into a saturated liquid (4-1). Next, it is directed to a pump, which will increase the pressure that the system works under (1-2), making it pass through the steam generator once again to finish the cycle. At the same time, mechanical work is produced in the ST (5), which is transformed into electrical power with a GE (6).

This study proposes to analyze an ORC plant thermodynamically in order to produce electricity [19]. The simulation consists of evaluating the ORC based on 14 different working fluids and detecting what the advantages of each fluid are. The comparison of the simulations focuses on thermal yield, net power produced, pump output, heat supplied, and exergy destroyed, both per machine and total, as well as the exergy efficiency. The objective is to identify the most suitable working fluid for these geothermal conditions.

2. Methodology

The Reference Fluid Thermodynamic and Transport Properties software program (REFPROP v.8.0)—created by the National Institute of Standards and Technology (NIST)—was used to collect the thermodynamic properties of the 14 fluids that were employed (Table 3). This software is capable of estimating the thermophysical properties of more than 80 pure substances, as well as their possible mixtures, mainly of coolants, hydrocarbons, and different natural gas compositions, and it provides tables and diagrams of them.

The operation conditions were set according to some of the area's parameters as well as to those of the technology that was used, such as the maximum temperature of the geothermal resource and the yearly average ambient temperature (19 ℃), which defines the condensation temperature. Likewise, a condensation turbine that used overheated steam at 46% pressure below the saturation pressure was considered. The saturation pressure of each fluid was measured and compared to the average ambient temperature to analyze the second law. The rest of the criteria can be seen in Table 4.

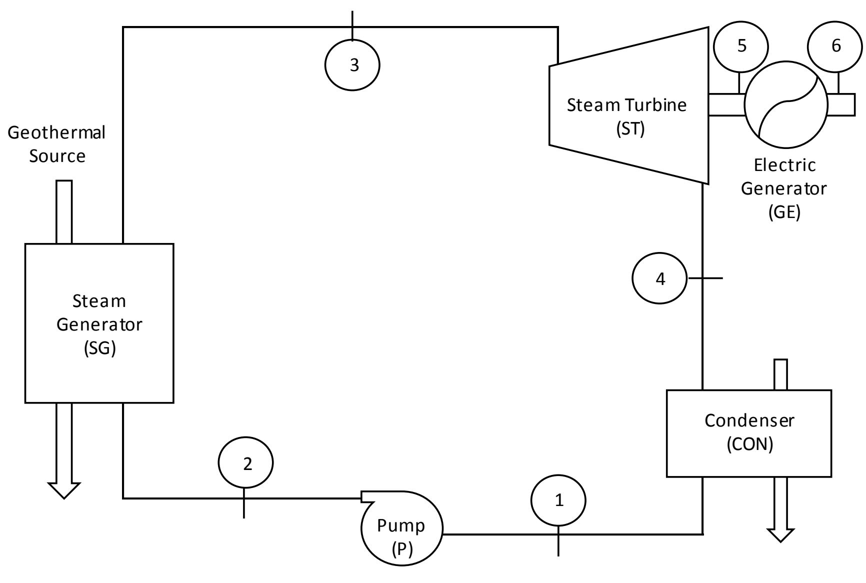

Fig. 2 Schematic diagram of the proposed ORC.

Table 3 Working fluids used in the ORC simulation.

No.	Working fluid	No.	Working fluid
1	Propane	8	n-Pentane
2	i-Pentane	9	R152a
3	Butane	10	R11
4	1-Butene	11	R12
5	R134a	12	R113
6	R141b	13	R114
7	R142b	14	R21

Table 4 Conditions and considerations for the ORC simulation.

Geothermal source temperature (ta)	92 ℃
Temperature difference in the SG	10 ℃
Temperature difference in the CON	10 ℃
Isentropic efficiency of the ST	85%
Isentropic efficiency of the P	80%
Efficiency of the GE	96%
Effectiveness of the SG	100%
Mass flow of the geothermal fluid (GF)	1 kg/s

The energy and exergy balances were carried out for each one of the involved components according to the following equations (Table 5), disregarding the kinetic and potential energy of the system at all times.

3. Results

The analysis showed significant differences between the values of the mass fluids. The working fluid with the highest demand was R114, with 1.355 kg/s, while the cycle with n-Pentane only produced a demand of 0.487 kg/s (Fig. 3). However, observing the rest of the analyzed parameters, as well as the net output power (Fig. 4), the heat supplied (Fig. 5), the working pressures (Fig. 6), the pump power (Fig. 7), and the energetic efficiency (Fig. 8), the working fluid that performed the best was R113.

Although R113 was among the WF that produced the greatest mass flow (1.197 kg/s), it also demands less power from the pump (0.074 kW), given that its working pressure interval is lower than all the others (DP = 0.077 MPa). In addition, it has the lowest operating pressures (0.052 MPa-0.129 MPa). It has also been observed that it is the WF that most uses geothermal heat from the source (221.94 kWt) and it provides more energy to be transformed into electrical power (13.04 kWe), finally obtaining the best thermal efficiency (5.87%) in comparison to the rest of the working fluids.

For the second law results, regarding the exergy that was destroyed, it can be observed that when employing R113 coolant, less exergy is destroyed in the steamer and in the pump. However, this does not

Table 5 Equations used for the ORC analysis.

Equation	No.
Pump	
$\dot{W}_P = \dot{m}_{FT}(h_2 - h_1)$	(1)
Steam generator	
$\dot{H}_A = \dot{m}_{FT}(h_3 - h_2)$	(2)
$\dot{H}_C = \dot{m}_{FG}(h_a - h_b)$	(3)
Steam turbine	
$\dot{W}_{ST} = \dot{m}_{FT}(h_3 - h_4)$	(4)
Condenser	
$\dot{Q}_{CON} = \dot{m}_{FT}(h_4 - h_1)$	(5)
Electric generator	
$\dot{W}_{EG} = (\dot{W}_{TV} - \dot{W}_B) * \eta_{GE}$	(6)
Physical exergy	
$\dot{E}x_i = \dot{m}[(h_i - h_0) - T_0(s_i - s_0)]$	(7)
Mass balance	
$\sum \dot{m}_{in} = \sum \dot{m}_{out}$	(8)
Relationship of mass flow rates	
$R(FT/FG) = \dot{m}_{FT}/\dot{m}_{FG}$	(9)
Energy balance	
$\sum \dot{E}_{in} = \sum \dot{E}_{out}$	(10)
Exergy balance	
$\dot{E}x_D = \sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \dot{W}$	(11)
Thermal efficiency	
$\eta_{th} = \frac{\dot{W}_{ST} - \dot{W}_P}{\dot{H}_C}$	(12)
Exergy efficiency	
$\eta_{Ex} = \frac{\dot{W}_{ST} - \dot{W}_P}{\dot{E}x_a - \dot{E}x_b}$	(13)

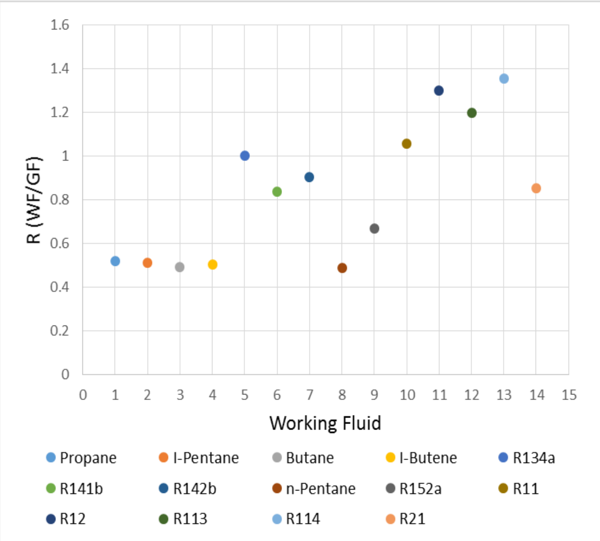

Fig. 3 Mass fluids needed for the ORC to operate.

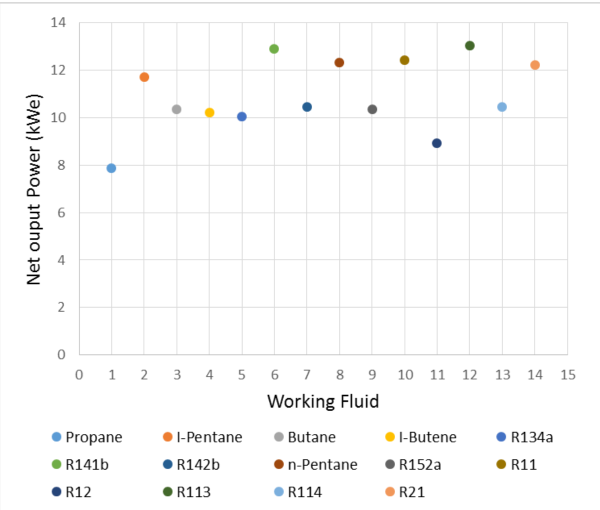

Fig. 4 Net output power for each of the 14 analyzed working fluids.

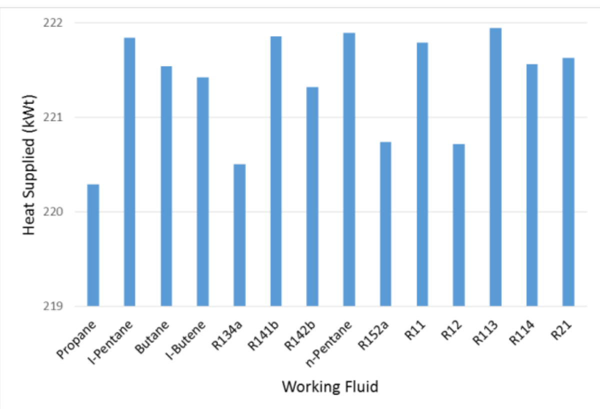

Fig. 5 Heat supplied or yielded to the ORC through the geothermal source.

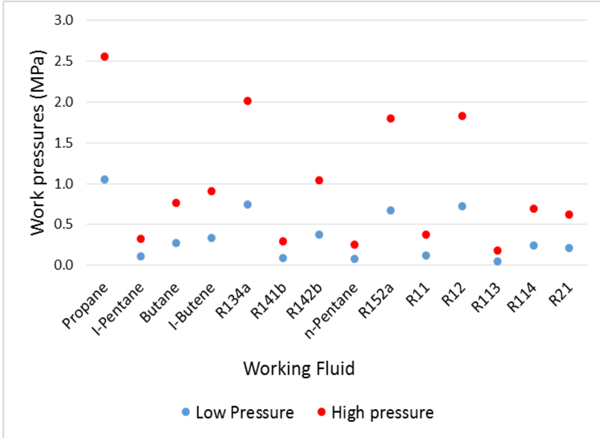

Fig. 6 Maximum and minimum operating pressures within the system for each of the fluids.

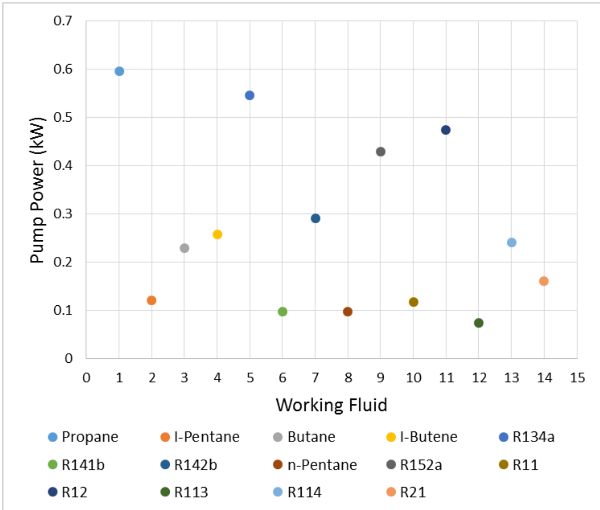

Fig. 7 Power needed by the pump for each of the working fluids.

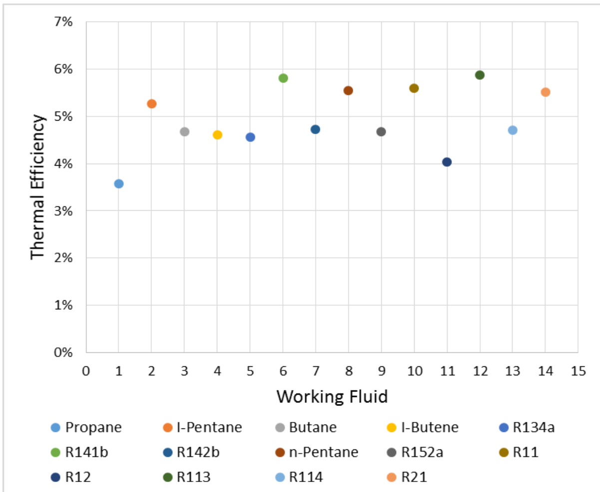

Fig. 8 Thermal efficiency for the ORC for each of the analyzed fluids.

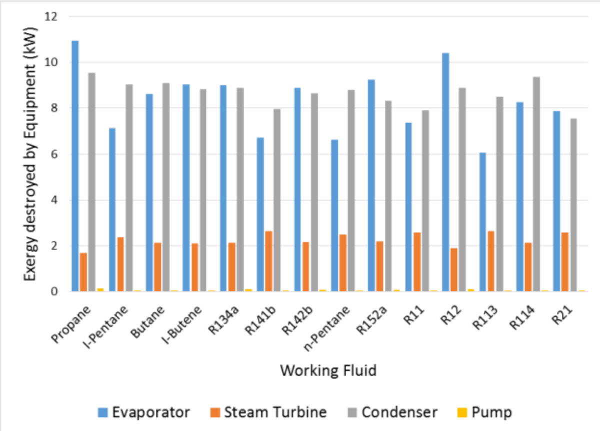

Fig. 9 Exergy destroyed per machine by each of the analyzed fluids.

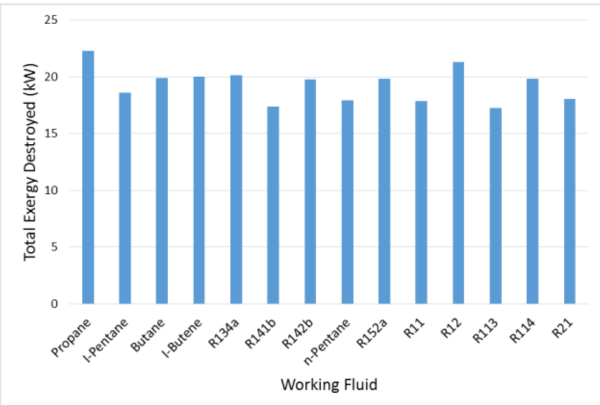

Fig. 10 Total exergy destroyed by the ORC plant by each of the analyzed fluids.

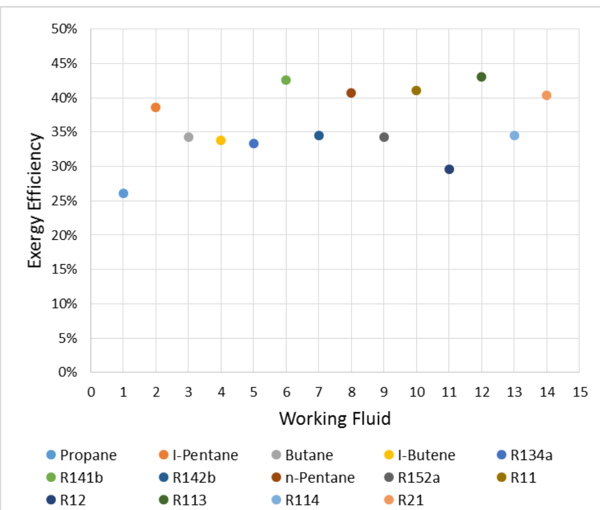

Fig. 11 Overall exergy efficiency of the ORC for each of the analyzed fluids.

occur in the cases of the steam turbine and the condenser (Figs. 9 and 10). Despite this, due to the high use of the exergy that was both supplied and used in the steam generator, the ORC has better exergy performance (Fig. 11).

ORC power plants provide reliable technology that has been distributed and applied in other parts of the world, like Germany and Italy, where modular package equipment from different brands (Siemens and Turboden, among others) has been implemented, which has mainly been used to take advantage of the heat given off in industrial processes.

A factor that should be taken into consideration in these types of technological proposals is that exploiting a geothermal resource will generate impacts that will affect the local environment. In the case of Los Negritos, there have been evaluations that show it to be an area with fragile sustainable development [21], and therefore, special care should be taken when carrying out this type of projects.

4. Conclusion

While not greater than 6%, the thermal output collected for the ORC plant—under the conditions of the environment and design proposed in this study—indicates that these types of plants are a possible alternative for generating electricity, given that they are capable of using low-temperature heat sources. With one or several plants like this, the region's demand could be supplied. Of all the analyzed fluids, R113 performed the best in comparison to the rest of the WFs in every respect, as it destroyed the least exergy. It is necessary to perform more detailed studies in order to identify the net efficiencies and potential of the maximum output, varying some conditions of the design and operation as well as estimating the costs of technology compared to the net power obtained, taking into account, at all times, international environmental measures and the preservation of local ecosystems and landscapes.

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