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Thermal Analysis of Organic Rankine Cycle Using Different Organic Fluids

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Abstract
A thermodynamic analysis of the Organic Rankine Cycle (ORC) is presented based on the first law of thermodynamics to find out the effect of the organic fluid selection on the cycle efficiency and power output. Different configurations of ORCs with and without Internal Heat Exchanger (IHE) are used. The criteria used to choose the optimum working fluid are discussed and many different organic fluids are compared in terms of the thermal efficiency and power output. The results obtained show that higher efficiencies are obtained for ORC with IHE configuration, and that the organic fluid R123 has the most favorable performance, for which the thermal efficiency of ORC is 14.2 and 13.28 with and without IHE, respectively. Moreover, the work output of ORC is about 50 kJ/kg, which is the highest when R123 is used as an organic fluid.

Keywords: *Geothermal, Rankine cycle, Organic fluids.*

1. Introduction
Economic growth, automation, and modernization mainly depend on the security of energy supply. The global energy demand is rapidly growing, and, presently, the worldwide concern is on how to satisfy this future energy demand. Long-term projections indicate that the energy demand will rapidly increase worldwide. In order to supply this increasing demand, fossil fuels have been used as the primary energy sources. However, fossil fuels emit greenhouse gases that highly affect the environment and the future generation [1].
Energy is an indispensable factor for the economic growth and development of a country. Energy consumption is rapidly increasing worldwide. In order to fulfill this energy demand, alternative energy sources and efficient utilization are being explored. The results of references 2-7 show that renewable energy resources are becoming more prevalent as more electricity generation becomes necessary and could provide half of the total energy demands by 2050.
Nevertheless, renewable energy sources such as solar, wind, hydro, biomass, and geothermal energy are very low-emission sources compared to the conventional fossil fuels. Renewable energy technologies are ideal solutions because they can contribute significantly to the worldwide power production with less emission of greenhouse gases [8-10]. The "sustainable future" scenario according to the International Energy Agency (IEA) shows that 57% of the world electricity will be provided by renewable energy sources by 2050. However, a long-term forecast and planning is required to achieve this ultimate target. Renewable energy-based power generation and the supply to the grid are the steps necessary to reach this goal and reduce the dependency on fossil fuels.
In the recent years, renewable energy resources have received enormous interest due to the increasing energy demand, depleting natural resources, and environmental concerns. Among the renewable energies, geothermal energy is a promising source due to its consistency and reliability, and is widely used as a reliable source of electricity generation. In comparison with alternative sources of energy production, geothermal power plants are among the most environmentally benign. The positive aspects of geothermal energy include a reduction of emissions, reduced water, and land use, along with economic feasibility. Geothermal energy is a renewable heat energy that comes from beneath the Earth's surface with temperatures varying from 50 ºC to 350 ºC. It can be in the form of steam, a two-phase mixture of steam and water or liquid water.
Geothermal energy has been presented for decades and identified as a good source of power production. The first demonstration on power

generation from a geothermal source was in 1904 at Larderallo, Italy [11]. In addition to the use of geothermal energy for electricity production [3], it can also be used for space cooling [12, 13] and freshwater production [14].

One of the most effective cycles in electricity production is the Rankine cycle. The performance of this cycle can be improved by coupling it with parabolic trough collectors to replace the closed feed-water heaters in the Rankine cycle [15]. In the context of geothermal power generation, Organic Rankine Cycles (ORCs) [16, 17] are adopted as eligible technologies since they have promising features such as simplicity of configuration, component availability, and a better economic return. Among the major types of geothermal power plants, the binary plants based on ORCs are becoming increasingly common. With the emergence of small binary power units as commercially viable plants, many reservoirs previously thought to be unsuitable for generating power because of low temperatures are now good candidates for development [18].

The operating principle of ORCs [19-23] is the same as that of the Rankine cycle, where the fluid is pumped to a boiler (evaporator), which then expands through a turbine, and is then condensed through a heat exchanger where it returns to its original state. ORC is named for the use of an organic fluid with a lower temperature boiling point. The fluid allows heat recovery from a lower temperature source such as a geothermal reservoir, as shown in figure 1, which shows the change of entropy with temperature.

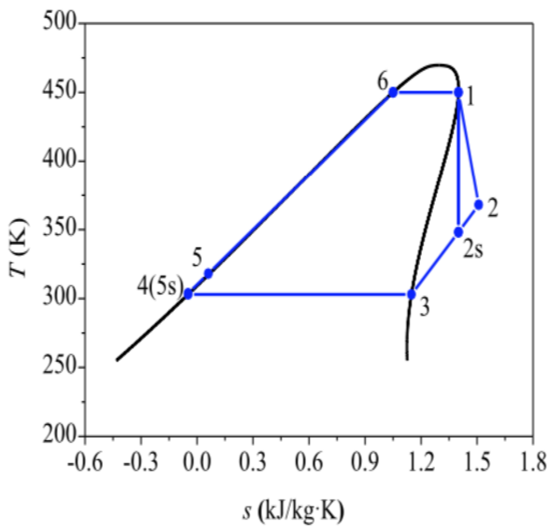

Figure 1. T-s diagram of an ORC [24].

Organic fluids usually have a low boiling point temperature and a high vaporization rate compared to water, which make them very attractive in producing power at a low heat source temperature when they are used in ORC power plants. The main objective of this work was to determine the best possible organic fluid of ORC, which results in the highest thermal efficiency and work output. Moreover, the previous results available in the literature are reported in this work to give an insight about organic fluids and their effect on efficiency with and without IHX configurations.

2. Thermodyanmic Analysis

A schematic diagram of an ORC power plant is shown in figure 2. Different organic fluids as working fluids for ORC power plant powered by geothermal energy source due to the low-grade temperature are required from the geofluid to vaporize the organic fluid, which flows into the evaporator (boiler).

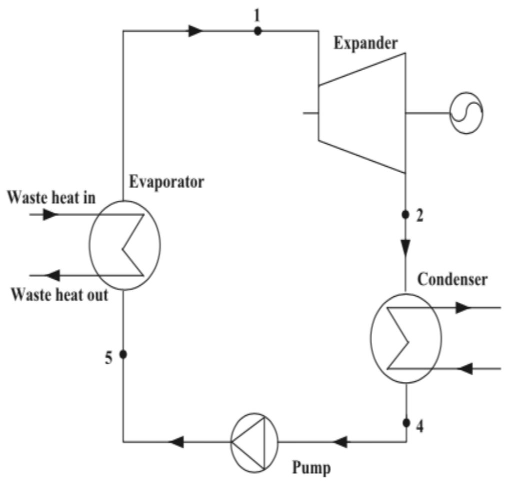

Figure 2. ORC configuration.

Expansion process (1-2): the vapor expands to generate power or work. An ideal assumption is the isentropic expansion. A practical expansion can be reflected by an isentropic efficiency, ηs. The power for expansion can be written as:

$$\dot{W}_e = \dot{m}_{wf}(h_1 - h_2) = \dot{m}_{wf}(h_1 - h_{2s})\eta_s \quad (1)$$

Condensation process (2-4): the superheated or saturated vapor is condensed into a saturated liquid in the condenser. The condensation heat is:

$$\dot{Q}_{cond} = \dot{m}_{wf}(h_2 - h_4) = \dot{m}_{aie}(h_{air,out} - h_{air,in}) \quad (2)$$

The pump power is expressed as:

$$\dot{W}_p = m\dot{m}_{wf}(h_5 - h_4) = \dot{m}_{wf}(h_{5s} - h_4)/\eta_p \quad (3)$$

Evaporation process (5-1): the organic liquid receives heat from the waste heat to form the saturated vapor at the evaporator outlet. The heat received from the heat source is:

$$\dot{Q}_{ev} = m\dot{m}_{wf}(h_1 - h_5) = \dot{m_{wh}}(h_{wh,in} - h_{wh,out}) \quad (4)$$

Thus the net power generated by ORC is:

$$\dot{W_{net}} = \dot{W}_t - \dot{W}_p \quad (5)$$

The ORC thermal efficiency is:

$$\eta_{thermal} = \frac{\dot{W}_{net}}{\dot{Q}_{ev}} \quad (6)$$

3. Results and Discussion

Table 1 summarizes the input information about the working fluids, while table 2 shows the results of the thermodynamic analysis for a given evaporator (boiler) temperature obtained in this work.

It is shown in table 2 that the best working fluid under the operating temperature of the evaporator is R601, which gives the highest efficiency and power output. A previous work [25] was used to study the effects of using different organic fluids for ORC with and without the internal heat exchanger, and the results of this work is shown in tables 3 and 4, where the best ORC performance was obtained using R123 as the working fluid. This difference is due to the different operating conditions used in this work.

Table 1. Critical temperatures and pressures of some organic fluids.

Working fluid	Formula	Tc (K)	Pc (MPa)
Hexane	C_6H_{14}	507.82	3.03
Isohexane	C_6H_{14}	497.7	3.04
R601	C_5H_{12}	469.7	3.37
R123	$C_2HCl_2F_3$	456.83	3.66
R234fa	$C_3H_3F_5$	427.16	3.65

Table 2. Results of ORC using different fluids.

Working fluid	Tev (k)	ηt (%)	Wnet (kJ/kg)
Hexane	432	12.1	46
Isohexane	437	12.05	47
R601	462	12.3	48.2
R123	446	13.28	50
R234fa	415	13	49.4

Table 3. Performance of different working fluids without heat exchanger.

Working fluid	Formula	η_t (%)	W_{net} (kJ/kg)
R113	$Cl_3F_3C_2$	13.09	47.87
R123	$C_2HCl_2F_3$	13.28	50.38
R601	C_5H_{12}	12.6	48.57

In order to compare the results obtained, another thermo-economic analysis was conducted, and the results for the three different working fluids using an ORC with an IHX [26] closely matched the previous results (table 5).

Another analysis conducted by [27] compared 3 different organic working fluids for ORC to obtain the thermal efficiencies and the power output, as shown in table 6.

Table 4. Performance of different working fluids with IHX.

Working fluid	Formula	η_t (%)	W_{net}(kJ/kg)
R113	$Cl_3F_3C_2$	14.45	47.87
R123	$C_2HCl_2F_3$	14.2	50.38
R601	C_5H_{12}	14.06	48.57

Table 5. Performance of different working fluids.

Working fluid	Formula	η_t (%)	W_{net} (kJ/kg)
R113	Cl3F3C2	14.33	47.38
R123	C2HCl2F3	14.02	49.58
R601	C5H12	14.21	48.52

Table 6. Performance of different working fluids.

Working fluid	Formula	η_t (%)	W_{net} (kW)
R134a	$C_2H_2F_4$	10.5	38.857
R246fa	$C_2HCl_2F_3$	11.3	36.3816
R245fa	$C_3H_2F_6$	15.1	39.962

The type b1 configuration corresponds to the saturated vapor at the turbine inlet, type b2 corresponds to the liquid-vapor mixture at the turbine exit, and b3 type corresponds to the superheated vapor at the turbine inlet and exit. As it can be seen in table 6 and the previous results, the choice of the working fluid depends on the operating conditions, cost of the plant, safety, and environmental impact.

The working fluid should be chosen carefully depending on the working conditions, high critical temperature and maximum pressure, low triple-point temperature, condenser pressure that is not too low, high enthalpy of vaporization, saturation dome that resembles an inverted U, high thermal conductivity (good heat transfer characteristics), and other properties such as non-toxic, inert, inexpensive, and readily available.

Table 7. Comparison of ORC with and without an IHX [28].

Comparison of ORC with pressures up to 20 bar without (-IHE) and with internal heat exchanger (+IHE)										
Substance	**Cycle type**	T_c ($°C$)	P_c (bar)	T_3 ($°C$)	T_4 ($°C$)	P_{min} (bar)	P_{max} (bar)	$\dot{m}$ ($\frac{kg}{s}$)	η_{th}% (-IHE)	η_{th}% (+IHE)	**x**
R125	b1	66.18	36.3	40.06	30.00	15.64	20.0	400.37	2.32	-	0.99
R125	b3	66.18	36.3	100.00	91.92	15.64	20.0	246.3	2.36	2.36	-
R142a	b1	72.73	37.64	43.59	30.00	14.40	20.0	197.92	3.14	-	0.98
R143a	b3	72.73	37.64	100.00	87.37	14.40	20.0	127.89	3.31	4.36	-
R32	b1	78.11	57.83	31.36	30.00	19.31	20.0	1062.6	0.36	-	0.99
R32	b3	78.11	57.83	100.00	97.75	19.31	20.0	682.78	0.42	0.53	-
RE125	b2	81.34	33.51	57.67	31.50	10.11	20.0	145.17	5.67	-	-
RE125	b3	81.34	33.51	100.00	79.04	10.11	20.0	103.11	5.77	7.34	-
R1270	b1	92.42	46.65	48.54	30.00	13.09	20.0	69.33	4.28	-	0.98
R1270	b3	92.42	46.65	100.00	81.28	13.09	20.0	49.11	4.53	5.51	-
R290	b1	96.65	42.50	57.14	30.00	10.79	20.0	48.77	5.91	-	0.99
R290	b3	96.65	42.50	100.00	76.02	10.79	20.0	36.10	6.11	7.32	-
R143a	b1	101.32	40.56	67.75	30.00	7.72	20.0	68.55	9.20	-	-
R152a	b1	113.50	44.95	72.59	30.00	6.88	20.0	3.01	8.82	-	0.96
R152a	b3	113.50	44.95	100.00	53.84	6.89	20.0	2.86	9.22	9.7	-
CF3I	b1	123.29	39.53	58.24	30.00	5.65	20.0	1.58	10.63	-	0.96
CF3I	b3	123.29	39.53	100.00	39.60	5.65	20.0	3.54	10.93	-	-
RC270	b3	124.65	54.90	100.00	41.63	8.23	20.0	2.18	8.86	-	-
Re170	b1	126.85	52.40	75.10	30.00	6.73	20.0	1.58	9.38	-	0.98

4. Conclusion

In this work, an energy analysis of an ORC power plant was presented using different organic fluids. Choosing the right working fluid for ORC is an important step, which depends on several factors such as the source temperature, critical temperature and pressure, enthalpy of vaporization, and heat transfer characteristics. The other properties include environmental sustainability, ozone depletion potential (ODP), global warming potential (GWP), safety (non-toxic, non-flammable, non-corrosive), and stability of the working fluid. In this work, R601 was chosen instead of R123 in the first scenario, and R123 instead of R601 in the second one. This can be due to different reasons such as the cost or availability of R123 as it is a common refrigerant. Another cause is that R601 has zero ODP and GWP, and is a dry fluid that avoids blade erosion and corrosion. R123 as an organic fluid showed the best performance of ORC in terms of thermal efficiency and work output. This work recommends the use of IHX with an ORC power plant to improve the performance of the cycle. Due to the low temperature required to run the ORC power plants, it is recommended to run such a power plant with a low enthalpy geothermal heat source.

Nomenclature

$\dot{W}$	Power output, kW
$\dot{m}$	Mass flow rate, kg/s
h	Enthalpy, kJ/kg
η_s	Isentropic efficiency
$\dot{Q}$	Heat transfer rate, kW

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