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AN EXAMINATION OF POWER GENERATION FROM ABANDONED PETROLEUM RESERVOIRS USING ORGANIC RANKINE CYCLE

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ABSTRACT

Most of the wells were plugged due to a decline in oil and gas productivity, while other wells were exploratory. In cases, Abandoned oil and gas wells contain abundant geothermal energy, which can be retrofitted to a novel geothermal system for different utilizations without high-cost drilling. Thus, recently, some researchers have focused on the evaluation of the performance of thermal energy extraction from Abandoned oil and gas wells (AOGW) using Organic Rankine cycle (ORC) systems. Each study applied different working conditions, power scales and cycle configurations; hence an assessment of working fluids is given for specific cases. As a result, no single working fluid has been identified that would meet an entire heat source temperature level. This motivated us to examine various substances for use as working fluids for subcritical ORC systems operating in the medium-temperature range (100–150°C). This examination was based on the first and second law of thermodynamics, and parameters such as thermal efficiency, first law, and second law efficiency were evaluated. It was demonstrated that the organic fluids examined could be used to generate power using low-temperature waste heat. Organic fluids do not need to be superheated since the cycle thermal efficiency remains approximately constant when the inlet temperature of the turbine is increased. However, using the second law analysis superheating the organic fluids increases the irreversibility. Therefore, organic fluids must be operated at saturated conditions to reduce the total irreversibility of the system. The thermal efficiency of ORC increases when the condenser temperature is decreased. Therefore, using ORC in locations with low ambient temperatures will be more effective. Organic dry fluids (R113, R227ea and isobutane) have better performance than wet fluids (R134a). This is because they do not condense after the fluid goes through the turbine as wet fluids do.

1.0 Introduction

In the past decades, fossil fuels played a central role in promoting social development. Most of the global energy consumption comes from oil, coal, and gas. However, the rate of fossil fuel consumption is much higher than that of exploitation, and the growing energy demand drives humans to explore alternative resources. Meanwhile, the burning of fossil fuels is the primary cause of environmental pollution like haze, global warming, and air contamination. As the rising energy demand and environmental issues become non-negligible problems demanding prompt solutions, the utilization of renewable and clean energy is a valid way to deal with energy and environmental problems. So, in recent years there has been an increasing interest in the use of renewable and clean energy resources such as solar energy, wind energy, geothermal energy, tidal energy and so on [1]. As a renewable energy source, geothermal energy has huge potential to power our world in a sustainable, reliable and environmentally friendly way[2]. Compared with other alternative sources of energy, such as solar or wind energy, the efficiency of geothermal energy does not depend on weather or climate conditions[1]. However, one of the primary obstacles to developing geothermal energy is the capital cost of drilling deep wells. The cost of drilling even can occupy 50% of the total cost of the geothermal project, and the market of geothermal energy applications would be expanded significantly if this problem could be solved. At the same time, in the petroleum industry, millions of oil wells have been abandoned and their leaking problem is a threat to the local environment [2, 3]. Statistics show that about 20–30 million oil wells have been abandoned around the world [4], and at least 1.2 million wells had been abandoned for the US in 1987 [5]. If the Abandoned Oil and Gas Wells can be retrofitted to the geothermal system for extracting thermal energy, not only the environmental risk can be reduced effectively, but also the geothermal utilizations will become cheaper without high-cost drilling. Therefore, many researchers begin to study Abandoned Oil and Gas Wells for heat extraction and power generation. Hence, ORC has emerged as a promising technology in future conservation energy and energy demands, by exploiting geothermal energy into electricity. One of the challenges of ORC is the selection of organic working fluid, it represents the main difference between ORCs and steam rankine cycle and is considered to be significantly important in maximizing the ORC overall efficiency[4]. The working fluids could be employed as pure or mixed fluids. To this purpose, the heat source at different temperature levels and the application influence significantly the proper selection of fluids and appropriate operating conditions[6]. Particularly, ORC is a key technology adopted to recover heat from various sources, both at low and at medium or high temperature. Davis and Michaelides[7, 8] firstly investigated the feasibility of using AOGW for power generation by ORC. They also retrofitted the well by using the coaxial WHE with outer diameter of 300 mm. In addition, instead of using water as working fluids in [9], an organic fluid, isobutene was proposed for geothermal extraction and power generation. In their study, a simple optimization study for power produced was performed with examining fluid injection pressure and flow rate. With the optimized injection parameters and inner pipe radius, the proposed system could produce approximately 3.4 MW of power. Based on the literature review above, the present study introduces an examination of power generation from abandoned petroleum reservoirs using a simple ORC and the analysis of the performance of basic ORC to produce electric power. This analysis was based on the first and second laws of thermodynamics, and parameters such as thermal efficiency, first-law, and second-law efficiency.

2.0 Organic Rankine Cycle (ORC)

ORC operates on the same principle as a conventional Steam Rankine Cycle that is to take heat from a heated source and transform it into useful work via four major components of the system that are discussed briefly in upcoming sections. The key difference between ORC and conventional Steam Rankine cycle is the working fluid which decides the efficiency, effectiveness, and adaptability of ORC.

Working fluid used in ORC is high volatile and low boiling temperature as compared to water at the same temperature due to which it is possible to even convert low grade heat energy into mechanical work. The value of enthalpy in wet saturated region (h_{fg}), global warming potential and thermal efficiency achieved decides either it should be selected or not. It is investigated that the use of ORC proves more beneficial on the places where the temperature of the exhaust gases is below than 310◦C as compared to the Steam Rankine Cycle [9]. The operating temperature range of ORC is 80℃ to 340℃ and even ORCs working down to the temperature under 73.3℃ is also reported. The US department of Energy funded the super truck program for exploiting the waste heat for better efficiency of engine fuel. Many industrial processes produce waste heat, for example the manufacturing of cement, textiles and electricity production [8]. Hence, the ORC power plants are widely used with waste heat in chemical industry, metal and mining, paper, and other industries. For geothermal systems the ORC is usually used to produce electric power. The principle of the ORC work is based on the thermodynamic Rankine steam-water cycle. Figure.1 shows the principle of the thermodynamic cycle work.

2.1 Components and Working of Orc:

The four major components that play a vital role in ORC as waste heat recovery system are:

1. Pump

2. Evaporator

2. Turbine

4. Condenser

The working fluid is pumped to the evaporator (1-2), where it transfers its heat to the organic fluid (2-4), which boils at low temperatures. After that it turns into a vapour-steam and under high pressure flows to the turbine, which performs mechanical work (4-5). The shafts of the turbine rotate, and electricity is generated. Then the exhausted vapour steam is condensed in the heat exchanger and returned into the liquid state (5-1), the cycle starts over again. Cooling of a condenser can be assured by water cooling systems.

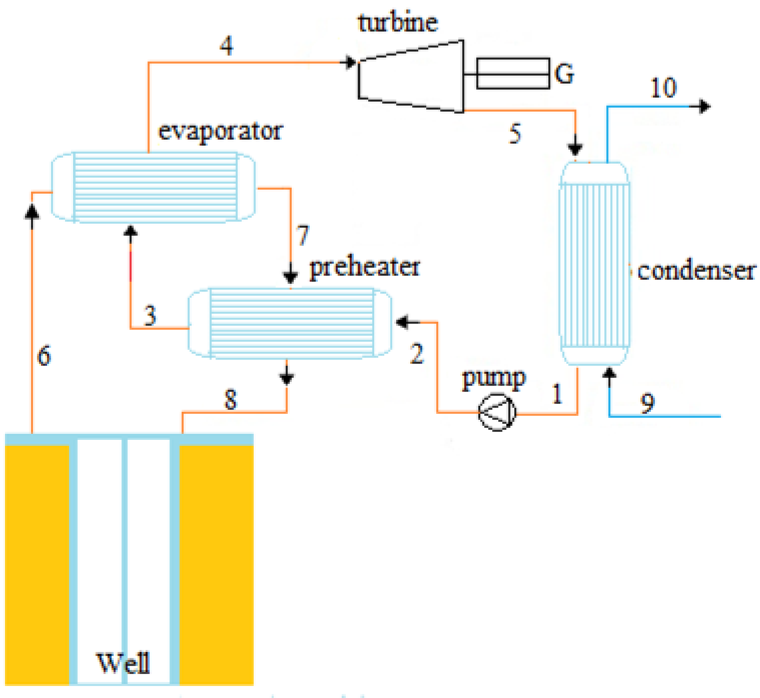


Figure. 1 Schematic diagram of the subcritical ORC

2.2 Organic Rankin Cycle Calculation

In this work, different organic fluids were chosen. The calculation was carried out with the following assumptions:

Efficiency of a generator and a pump are constant values, which do not depend on the operation conditions

The resistance in heat exchangers and pipelines is not taken into account;

There is no super cooling before a pump;

There is no heat exchange with the environment.

The efficiency of the cycle depends largely on the ambient temperature, which determines the temperature of the condenser. In this calculation, it was assumed that the condenser was cooled by water.

2.1 Energy and exergy analysis

The control volume energy and exergy analysis undergoing steady state process, without potential and kinetic energy, are expressed for each state as follows:

Liquid pressurization process (1-2):

This is a non-isentropic process. The power consumption of the pump can be expressed as follows:

$$\dot{W}_{pump} = \frac{\dot{m}_{wf}\,(h_{2,s} - h_1)}{\eta_{pump}} \tag{1}$$

The energetic and exergetic efficiencies of the pump were calculated as follows:

$$\eta_{I,P} = \frac{h_{2s} - h_1}{h_2 - h_1} \tag{2}$$

$$\eta_{II,P} = \frac{\dot{W}_p - \dot{I}_P}{\dot{W}_p} \tag{3}$$

Heat extraction process (2-4):

In this process, the heat is transferred to the working fluid across three zone heat exchanger. It can be imaginarily split into preheating section and evaporating section. The energy and exergy balance for the two segments are as follows:

preheater

$$\dot{m}_{wf}\,(h_3 - h_2) = \dot{m}_{hot}\,(h_7 - h_8) \tag{4}$$

$$\dot{I}_{PH} = \dot{E}x_1 + \dot{E}x_7 - \dot{E}x_3 + \dot{E}x_8 = \dot{m}_{wf}\,(\psi_2 - \psi_3) + \dot{m}_{hot}\,(\psi_7 - \psi_8) \tag{5}$$

evaporator

$$\dot{Q} = \dot{m}_{wf}\,(h_4 - h_3) = \dot{m}_{hot}\,(h_6 - h_7) \tag{6}$$

$$\dot{I}_{evap} = \dot{E}x_3 + \dot{E}x_6 - \dot{E}x_4 + \dot{E}x_7 = \dot{m}_{wf}\,(\psi_3 - \psi_4) + \dot{m}_{hot}\,(\psi_6 - \psi_7) \tag{7}$$

The energetic and exergetic efficiencies for pre-heater and evaporator were calculated by the following equations:

$$\eta_{I,PH} = \frac{T_3 - T_2}{T_7 - T_2} = \frac{T_7 - T_8}{T_7 - T_2} \tag{8}$$

$$\eta_{II,PH} = \frac{\dot{m}_{wf}\,(\psi_3 - \psi_2)}{\dot{m}_{hot}\,(\psi_7 - \psi_8)} \tag{9}$$

$$\eta_{I,evap} = \frac{T_4 - T_3}{T_6 - T_3} = \frac{T_6 - T_7}{T_6 - T_3} \tag{10}$$

$$\eta_{II,evap} = \frac{\dot{m}_{wf}\,(\psi_4 - \psi_3)}{\dot{m}_{hot}\,(\psi_6 - \psi_7)} \tag{11}$$

Power generation process state (4-5)

The power generated by the turbine during expansion is given as

$$\dot{W}_t = \dot{m}_{wf}\,(h_4 - h_5) \tag{12}$$

The expansion in the turbine deviates from ideal isentropic behaviour by isentropic efficiency

$$\dot{W}_t = \dot{m}_{wf}(h_4 - h_{5,s})\eta_t \tag{13}$$

The exergy balance for turbine is given by:

$$\dot{I}_{turbine} = \dot{E}x_4 - \dot{E}x_5 - \dot{W}_t = \dot{m}_{wf}(\psi_4 - \psi_5) - W_t \tag{14}$$

The energetic and exergetic efficiencies of the turbine were calculated as follows:

$$\eta_{I,t} = \frac{(h_4 - h_5)}{(h_4 - h_{5,s})} \tag{15}$$

$$\eta_{II,t} = \frac{\dot{W}_t}{\dot{W}_t + \dot{I}_t} \tag{16}$$

Condensation process (5-1):

In this process, the heat is rejected to cooling medium in condenser in order to condensate the working fluid and directs it in a pump intake. The amount of heat rejected is given by:

$$\dot{Q} = \dot{m}_{wf}(h_5 - h_1) = \dot{m}_{cw}(h_{10} - h_9) \tag{17}$$

The exergy balance for condenser is given by:

$$\dot{I}_{condenser} = \dot{E}x_5 + \dot{E}x_9 - \dot{E}x_1 - \dot{E}x_{10} = \dot{m}_{wf}(\psi_5 - \psi_1) + \dot{m}_{cw}(\psi_9 - \psi_{10}) \tag{18}$$

The energetic and exergetic efficiencies of the condenser were calculated by:

$$\eta_{I,condenser} = \frac{T_{10} - T_9}{T_5 - T_9} = \frac{T_5 - T_1}{T_5 - T_9} \tag{19}$$

$$\eta_{II,condenser} = \frac{\dot{m}_{cw}(\psi_{10} - \psi_9)}{\dot{m}_{hot}(\psi_5 - \psi_1)} \tag{20}$$

The cycle power output is determined by[10].

$$\dot{W}_{net} = W_t - W_p \tag{21}$$

And the total exergy lost in the cycle and plant were defined respectively as[10, 11]

$$\dot{I}_{cycle} = \sum_{all.component} \dot{I}_i = \dot{I}_p + \dot{I}_{HE} + \dot{I}_t + \dot{I}_c \tag{22}$$

$$\dot{I}_{plant} = \dot{I}_{cycle} + \dot{I}_{rej} + \dot{I}_{cs} = \dot{E}x_{in} - \dot{W}_{net} \tag{23}$$

Where the total exergy inputs to the ORC was determined by [11-13].

$$\dot{E}x_{in} = \dot{m}_{HT}\left[(h_{HT} - h_o) - T_o(S_{HT} - S_o)\right] \tag{24}$$

2.2 Performance analysis

The First- and Second-law efficiencies, based on the geothermal fluid state at the inlet of the primary heat exchanger and with respect to the reference temperature To, were defined respectively as[11-13]

$$\eta_I = \frac{\dot{W}_{net}}{\dot{m}_{HT}(h_{HT} - h_o)} \qquad (25)$$

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{m}_{HT}\left[(h_{HT} - h_o) - T_o(S_{HT} - S_o)\right]} \qquad (26)$$

Based on energy input to the cycle, the first- and second-law efficiency were given by [11-14]

$$\eta_{I,2} = \frac{\dot{W}_{net}}{\dot{m}_{HT}(h_{HT} - h_{rej})} = \frac{\dot{W}_{net}}{\dot{m}_{wf}(h_{wf,out} - h_{wf,in})} \qquad (27)$$

$$\eta_{II,2} = \frac{\dot{W}_{net}}{\dot{m}_{HT}[(h_{HT} - h_{rej}) - T_o(S_{HT} - S_{rej})]} \qquad (28)$$

The performance of a geothermal power plant can also be evaluated using the cycle effectiveness, which represents the effectiveness of heat transfer to the cycle from the hot source, as [11-14]

$$\varepsilon = \frac{\dot{W}_{net}}{\dot{m}_{wf}[(h_{wf,out} - h_{wf,in}) - T_o(S_{wf,out} - S_{wf,in})]} \qquad (29)$$

3.0 Results and Discussion

The fundamental purpose of this work is to carry out sensitivity analysis of important thermodynamic parameters such as turbine entry temperature and condensation temperature. The effect of these parameters on net work output, thermal efficiency, first and second law efficiency is examined. Thermodynamic assessment of different working fluids under two conditions of turbine inlet temperature and condensation temperature is carried out using Engineering equation solver (EES). In this particular investigation, the state of the fluid at the turbine inlet is saturated vapor. Working fluids used in this study are dry, wet and isentropic fluids as presented in Table 1, there is no necessity of superheating before expansion. The input parameters are tabulated in table 2.

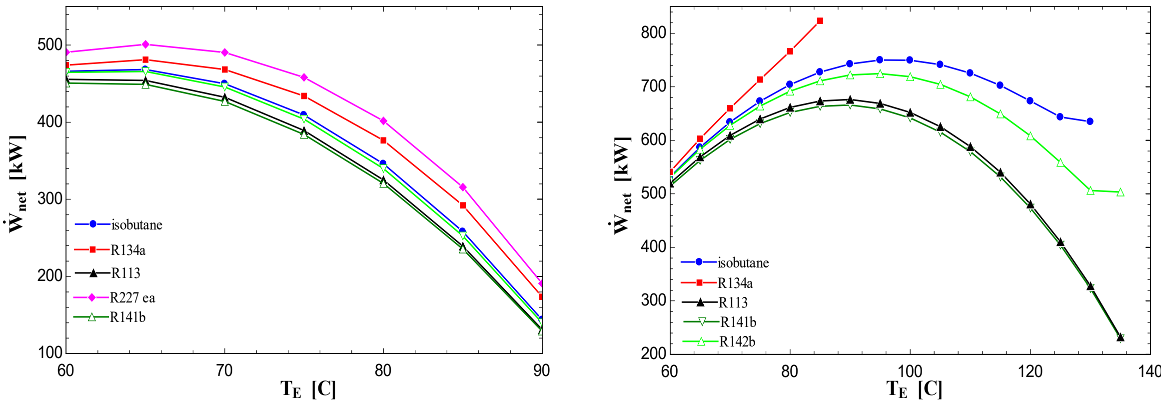
Table. 1 Properties of the organic fluids used in this investigation.

Working fluid	Type	Molecular weight (Kg/mol)	Critical properties		
			Bp(°C)	Tc(°C)	Pc(MPa)
R134a	wet	102.03	-26.07	101.06	4.059
R113	dry	187.38	47.59	214.06	3.392
R227ea	dry	170.03	-°16.34	101.75	2.925
R141b	isentropic	116.94	32.05	204.35	4.212
R142b	isentropic	100.49	-9.12	137.11	4.055
Isobutane	dry	58.12	-11.61	134.7	3.64

Table. 2 input parameters.

Input parameters	Value
Heat source temperature	100-150ºC
Heat source mass flow rate	1.7 (kg/s)
Turbine isentropic efficiency	0.8
Pump isentropic efficiency	0.9
Condensing temperature	29ºC
Pinch point temperature difference	5ºC

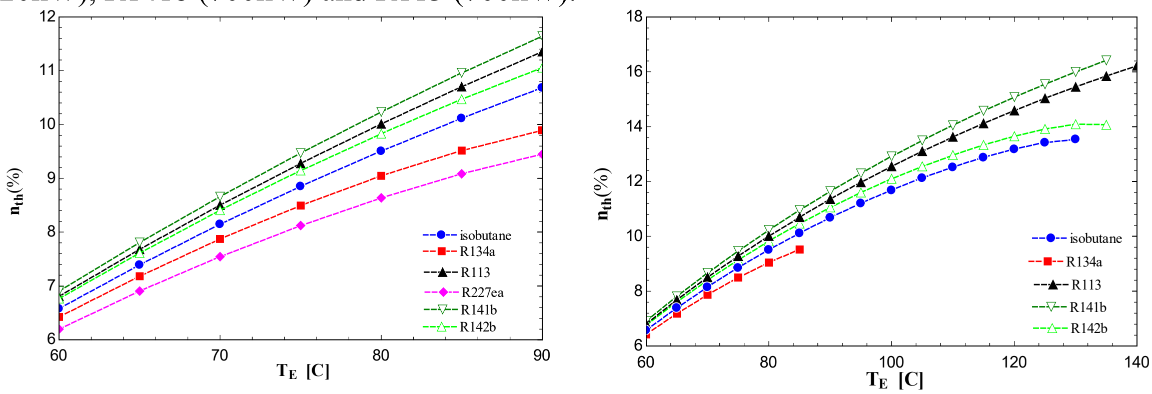
Variation of net work output with increase in turbine inlet temperature is depicted in figure 2-a and figure 2-b respectively. Also, impact of turbine entry temperature on thermal efficiency is illustrated in fig 5. The turbine inlet temperature was varied from 60 ˚C to 130 ˚C with a 5ºC step.



(a) (b)

Figure. 2 cycle power output for hot source temperature of (a) 100ºC and (b) 150ºC

Increasing turbine inlet temperatures lead to increase net power produced for the cycle. The reason of increasing of net power produced by ORC cycle is that heat input to the cycle takes place at high temperature. When the turbine inlet temperature raises, turbine outlet temperature increases. Hence, heat source temperature of ORC increases as well. This situation increases net power produced. Among these working fluids, the results indicate that isobutane exhibits the largest amount of work (750kW) in the temperature range (60-135oC) followed by R142b (720kW), R141b (700kW) and R113 (700kW).

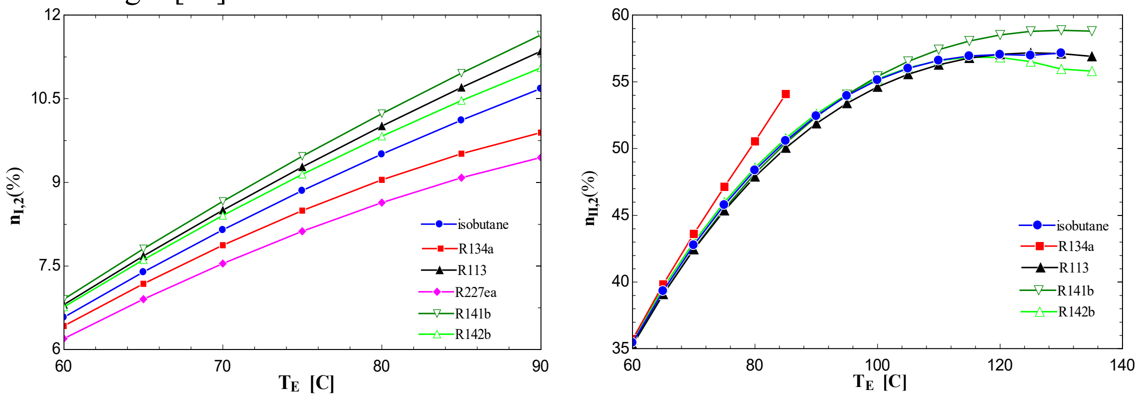


(a) (b)

Figure. 3 Thermal efficiency for subcritical ORC cycle at (a) 100ºC and (b)150ºC.

The variation of cycle thermal efficiency with the turbine inlet temperature was illustrated in figure 3. Unlike the cycle power output, the thermal efficiency showed an increase with the turbine inlet temperature. It was noticed that the organic fluids with high boiling point temperature, such as R141b (16%) ,R113(around 16%) and R142b (14%), had the best performance among the selected organic fluids, while both R134a and R227ea exhibits smallest thermal efficiency (10%) at lower turbine inlet temperature.

Based on the energy input to the cycle, the First and second law efficiencies were represented in Fig. 4. As the turbine inlet temperature increased, both first- and second law efficiencies increase. The noticeable lower First law efficiency (Fig. 4a) can be attributed to the large difference in temperature between the hot source and the organic fluid entering the primary heat exchanger [21].



(a) (b)

Figure. 4 (a) First- and (b) Second-law efficiency based on energy input to the ORC.

The cycle effectiveness which measures both quantitatively and qualitatively the amount of available energy to be transferred from the heat source to the organic fluid were plotted in Fig. 5, as a function of the turbine inlet temperature. The Second law efficiency and the cycle effectiveness as presented by Fig. 4-b and Fig. 5, respectively, were detected to yield an optimal turbine inlet temperature beyond which no substantial increase in both the Second-law efficiency and cycle effectiveness was noticeable. For all selected working fluid, only a marginal difference in the cycle effectiveness was observed. R141b showed better conversion of the thermal energy through the whole temperature range

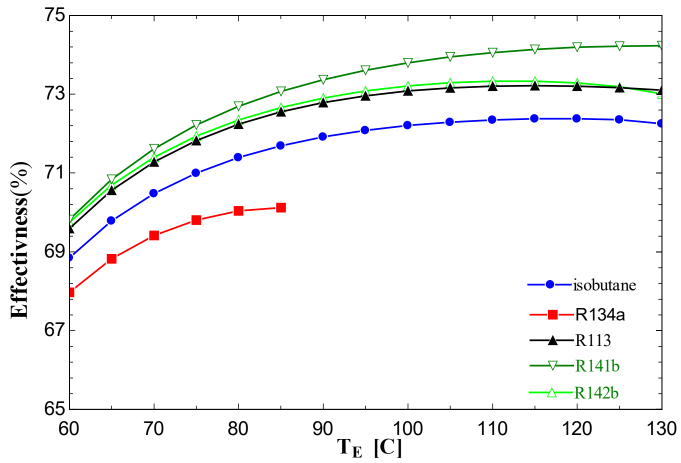


Figure. 5 cycle effectiveness

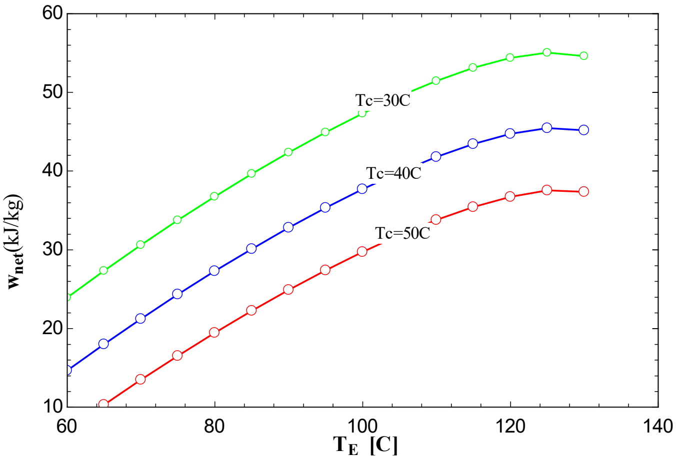


Figure. 6 Variation of the cycle power output with the condensing temperature

For a given temperature of the heat source and pinch point, the reduction in condensing temperature yielded higher cycle power output and lower optimal turbine inlet temperature (Fig. 6). Although a significant increase in the cycle power output was obtained due to the increasing enthalpy difference in the expansion process, a substantial increment in the pumping power requirements was, however, observed. This constraint determines the choice of cycle condensing temperature which depends on the site environmental conditions, capital costs and the stability of the organic fluid.

4.0 Conclusions

This study presents an examination of power generation from abandoned petroleum reservoirs using a simple ORC and the analysis of the performance of basic ORC to produce electric power. This analysis was based on the first and second laws of thermodynamics, and parameters such as thermal efficiency, first, and second laws efficiency. It was demonstrated that the organic fluids examined could be used to generate power using low-temperature waste heat. Organic fluids do not need to be superheated since the cycle thermal efficiency remains approximately constant when the inlet temperature of the turbine is increased. However, using the second law analysis it can be seen that superheating the organic fluids, increases the irreversibility. Therefore, organic fluids must be operated at saturated conditions to reduce the total irreversibility of the system. The results indicate that isobutane exhibits the largest amount of work in the temperature range (60-135oC) followed by R142b, R141b and R113. As for thermal efficiency, the organic fluids, such as R141b (16%), R113 (around 16%) and R142b (14%), had the best performance among the selected organic fluids, while both R134a and R227ea exhibits smallest thermal efficiency (10%) at lower turbine inlet temperature. Moreover, the thermal efficiency of ORC increases when the condenser temperature is decreased. Therefore, using ORC in locations with low ambient temperatures will be more effective. Among the selected fluids, R141b chosen as the best working fluids since it has higher work of 700kW and highest efficiency among its group giving up to 16%. Moreover, Organic dry fluids (R113, R227ea and isobutane) have better performance than wet fluids (R134a). This is because they do not condense after the fluid goes through the turbine as wet fluids do. To sum up, extracting heat from abandoned oil and gas wells is feasible and can provide about 0.7 MW of electric power by using an ORC system.

5.0 References

[1] Hammons, T.(2004),Geothermal power generation worldwide: Global perspective, technology, field experience, and research and development, Electric Power Components and Systems, vol.32. 529-553.
[2] Thiessen, R.J., G. Achari.(2017),Abandoned oil and gas well site environmental risk estimation, Toxicological & Environmental Chemistry, vol.99. 1170-1192.
[3] Kotler, S.(2011),Abandoned oil and gas wells are leaking, Z Magazine, https://zcomm. org/zmagazine/abandonedoil-and-gas-wells-are-leaking-by-steven-k otler.
[4] Chen, H., D.Y. Goswami, E.K. Stefanakos.(2010),A review of thermodynamic cycles and working fluids for the conversion of low-grade heat, Renewable and sustainable energy reviews, vol.14. 3059-3067.
[5] Muhammad, U., M. Imran, D.H. Lee, B.S. Park.(2015),Design and experimental investigation of a 1 kW organic Rankine cycle system using R245fa as working fluid for low-grade waste heat recovery from steam, Energy Conversion and Management, vol.103. 1089-1100.
[6] Vélez, F.(2014),Selecting working fluids in an organic Rankine cycle for power generation from low temperature heat sources, Dyna, vol.81. 173-180.
[7] Davis, A.P., E.E. Michaelides.(2009),Geothermal power production from abandoned oil wells, Energy, vol.34. 866-872.
[8] Davis, A.(2009),Geothermal power production from abandoned oil wells (Master's thesis), USA: The University of Texas at San Antonio.
[9] Kujawa, T., W. Nowak, A.A. Stachel, 2004, Utilization of existing deep geological wells for acquisitions of geothermal energy, in: Thermal Sciences 2004. Proceedings of the ASME-ZSIS International Thermal Science Seminar II, Begel House Inc.
[10] Aljundi, I.H.(2011),Effect of dry hydrocarbons and critical point temperature on the efficiencies of organic Rankine cycle, Renewable Energy, vol.36. 1196-1202.
[11] Kanoglu, M., A. Bolatturk.(2008),Performance and parametric investigation of a binary geothermal power plant by exergy, Renewable Energy, vol.33. 2366-2374.
[12] Subbiah, S., R. Natarajan.(1988),Thermodynamic analysis of binary-fluid Rankine cycles for geothermal power plants, Energy conversion and management, vol.28. 47-52.
[13] DiPippo, R.(2004),Second Law assessment of binary plants generating power from low-temperature geothermal fluids, Geothermics, vol.33. 565-586.
[14] Kanoglu, M.(2002),Exergy analysis of a dual-level binary geothermal power plant, Geothermics, vol.31. 709-724.