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Combined Solar-Geothermal Power Generation using Organic Rankine Cycle

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Abstract

This research investigates the possibility of power generation from geothermal and solar heat resources in Jordan using Organic Rankine Cycle (ORC). A comprehensive thermodynamic modelling and analysis is done in order to choose the appropriate fluid for the considered application.

Fluid selection process using EES software was conducted on sixteen fluids taking into account high side and low side temperature and pressure to be the most important parameters. A step by step thermodynamic modelling with the aid of both EES and CHEMCAD software was conducted simultaneously. Several improvements have been done on the cycle to achieve the most economical and efficient design. For the selected cycle, different components were sized and defined.

It was found that R600 is the most suitable fluid for application under study. The use of geothermal water as a heat source was found insufficient to generate power due to low temperature of the geothermal water. The open feed heater solar and geothermal Organic Rankine Cycle was found to be the most suitable for power generation for the selected site conditions.

Keywords: *Geothermal Energy, Solar Energy, Organic Rankine Cycle, Combined Geothermal-Solar, Organic Fluid Selection*.

1. Introduction

The Hashemite Kingdom of Jordan occupies a strategic location in the Middle East at an important crossroads for regional electrical energy integration. It is a developing non-oil producing country, where its energy requirements are obtained by importing oil from neighboring countries. The cost of importing energy creates a heavy financial burden on the national economy. Furthermore, the levels of electricity consumption are expected to double in the next 15 years. Renewable energy applications in Jordan include solar water heaters, solar photovoltaic, wind farms, hydropower and biogas. The total contribution of renewable energy in Jordan is about 3% of the total energy mix. The national energy strategy aims to integrate renewable energy in the energy system by allocating 7% of the total energy from renewable energy sources within the next 7 years. Moving forward looking for new energy technologies that can decrease our dependence on fossil fuels are needed. Organic Rankine Cycle (ORC) seems to be an important technology that can be used in future. It has a wide variety of applications that include power generation form low grade temperature energy sources. The cycle is compatible with a variety of heat sources such as exhaust, industrial process waste heat, geothermal energy sources, and solar energy.

In the past twenty years, because of its feasibility and reliability, Organic Rankine Cycle has received widespread attentions and researches [1]. ORC is a technology that can convert thermal energy at relative low temperatures in the range of 60 to 350 °C to electricity and can therefore play an important role to improve the energy efficiency of new or existing applications. Beside industrial waste heat, alternative heat sources such as solar and geothermal energy as well as biomass ORC can be applied. Zahra et al modeled and optimized an Organic Rankine Cycle for diesel engine waste heat recovery. In their work four refrigerants including R123, R134a, R245fa and R22 are selected and studied as working fluids. Then, the fast and elitist NSGA-II (Non-dominated Sorting Genetic Algorithm) is applied to maximize the thermal efficiency and minimize the total annual cost (sum of investment cost, fuel cost and environmental cost) simultaneously [2]. A two-stage organic Rankine cycle concept with internal heat recovery was presented by Dominik et al [3]. Leonardo studied a 100 kW_e hybrid plant consisting of gasification system, solid oxide fuel cells and Organic Rankine Cycle. More than hundred fluids are considered as possible alternative for the organic cycle using non-ideal equations of state (or state-of-the-art

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equations of state). A genetic algorithm is employed to select the optimal working fluid and the maximum pressure for the bottoming cycle [4]. The technical and economic feasibility of converting waste heat from a stream of liquid kerosene which must be cooled down to control the vacuum distillation temperature was investigated by H.C. Jung et al. The operating conditions and performance of the ORC system were evaluated with eight potential refrigerants and refrigerant mixtures such as R123, R134a, R245fa, isobutane, butane, pentane, an equimolar mixture of butane and pentane, and a mixture of 40% isobutane and 50% butane on a mole basis. A financial model was established for the total plant cost [5]. The thermodynamic performance of the ORC with a wet cooling system is analyzed using hydrocarbon working fluids driven by geothermal water from 100 °C to 150 °C and reinjection temperatures not less than 70 °C [6]. A thermodynamic modelling study of the utilization of an existing geothermal low-temperature heat source situated at Waddan city in Libya showed that the suggested station can provide Waddan city and surrounding villages with their demand of electrical and thermal energy [7].

The main difference between organic fluids and water is the lower evaporation energy of the former, so less heat is needed to evaporate the organic fluid. This ensures that low temperature waste heat of 60 to 100°C can be used as a heat source to the ORC installation. Accordingly, ORC is extremely suitable for waste heat recuperation in the industry and low temperature geothermal sources.

The selection of a suitable working fluid is not that easy. For most of the organic fluids vapour tables and saturation curves are unknown. Without the knowledge of the saturation pressures and temperatures it is not possible to evaluate the suitability of a fluid in any given application. Depending on the type of heat source (hot water, exhaust gases, geothermal) and its temperature level, a suitable working fluid with appropriate evaporation and condensing temperatures has to be selected.

In order to investigate the possibility of power generation from geothermal resources in Jordan, data from literature has been analyzed. A combined low grade temperature heat resource that exists in Jordan in the form of hot water springs, average temperature and flow rates of several springs have been studied.

The location of nearly all the thermal springs and the hot boreholes are dictated by their proximity to the Dead Sea Rift. Thermal springs are distributed along the eastern escarpment of the Dead Sea Rift for distance about 200 km, from Mukheibeh thermal field in the north to Afra and Burbeitta thermal field in the south [8].

2. FLUID SELECTION

The selection of working fluids has a great effect on the system operation conditions; its efficiency and power generation. Working fluids have also environmental impact.

In this research a procedure has been proposed to compare the different working fluids. Theoretical performances as well as thermodynamic and environmental properties of 16 organic fluids have been comparatively assessed for use in low-temperature solar and geothermal Organic Rankine Cycle systems. Efficiencies, pressure ratio, toxicity, flammability, ODP and GWP were used to compare different working fluids. This process was very helpful in selecting the most suitable fluids that match design criteria.

After selecting the most appropriate fluids, a detailed analysis for these fluids including its operating pressures as well as the efficiency and expander output work and the expander pressure ratio was carried out.

2.1. Preliminary selection

The basic Rankine cycle was used as a base to compare the different working fluids, since it gives the highest possible work and efficiency that can be achieved. Boiler pressure, condenser pressure and turbine inlet temperature were varied; consequently efficiency and work output were recorded and considered as the two main parameters for working fluid selection. Heat source temperature was varied as follows 60 °C (low), 120 °C (medium) and 180 °C (high).

Boiler pressure was varied while the condenser pressure was held constant. The work and efficiency vs. boiler pressure were plotted to see the highest work output and efficiency achieved for the three respective regions. Then condenser pressure was varied over the acceptable range for condenser to be used. Finally; boiler pressure was held constant while the work and efficiency for the three regions has been drawn. This process was done for the sixteen fluids that have been chosen to find suitable fluids for ORC applications. Table (1) summarizes the ranges for the boiler pressure, condenser pressure and turbine inlet temperature.

Table 1. Organic Rankine Cycle parameters and their ranges

Parameter	Range	
	Minimum	Maximum
Boiler Pressure (kPa)	500	2500
Condenser Pressure (kPa)	50	150
Turbine Inlet Temperature (kPa)	60	180

A sample of the preliminary fluid selection is shown below as it has been applied to R410a fluid.

Refrigerant 410a:

The first organic working fluid that was explored is the refrigerant R410a. The T-s diagram of the fluid with pressure lines at 50, 150, 500, and 2500 kPa is shown in Figure (1). It is clear from the figure that R410a has low boiling points under reasonable pressure

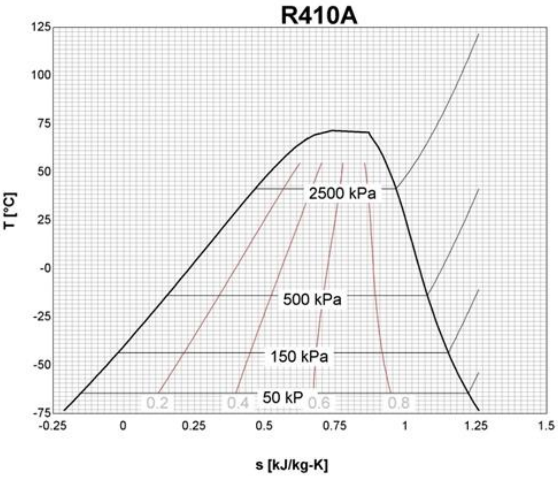

Figure 2. Temperature Entropy diagram for R410a

R410a is used to explore the parameters of the basic Rankine cycle. The sixteen fluids were also explored in the same manor. R410a will be discussed in detail in order to give an over view of the procedure used for fluid selection. For this analysis, one of the state points is pinned to the vapour dome of the working substance while the other was in the superheating region. This means that at the entrance of the expander, the fluid is in the superheating region (superheated vapour) and prior to entering the pump, it has a quality of zero (saturated liquid).

The first parameter whose effect on the cycle was studied was the boiler pressure; it was varied from 500 to 2500 kPa as shown in figure (3). The condenser pressure was kept constant at 50 kPa and a temperature of 60 °C. From figure (3) it can be seen that as the boiler pressure increases the efficiency increases. The work output reaches a maximum value then it becomes constant. The maximum efficiency that was achieved is 27.5 % while the maximum work output is around 95 kJ/kg. It can be seen that the boiler pressure and efficiency have a linear relationship but that doesn't come without drawbacks, since the increased inlet pressure requires a more expensive expander design.

The next parameter that was studied is the condenser pressure which affects the cold side temperature. The boiler pressure is held at 1500 kPa. The cold side temperature is controlled by the ambient temperature, it can be seen from figure (4) that as condenser pressure increases over the selected range the efficiency and work output decrease. This shows an expected behaviour since the difference across the expander pressure decreases. However; there is a limit to how much the pressure can be decreased. The condenser temperature which must be in an acceptable range that is close to ambient temperature.

The same procedure was performed for the medium and high temperature ranges. The results are shown in figures (5a) and (5b) respectively, where the boiler pressure was varied from 500 to 2500 kPa and the condenser pressure was held constant at 50 kPa, while the turbine inlet temperature for medium and high ranges was taken at 120 °C and 180 °C respectively. It is seen that there is a proportional relationship between the boiler pressure with the efficiency and work output, so in order to achieve the highest efficiency and work output the turbine inlet pressure must be taken as high as possible.

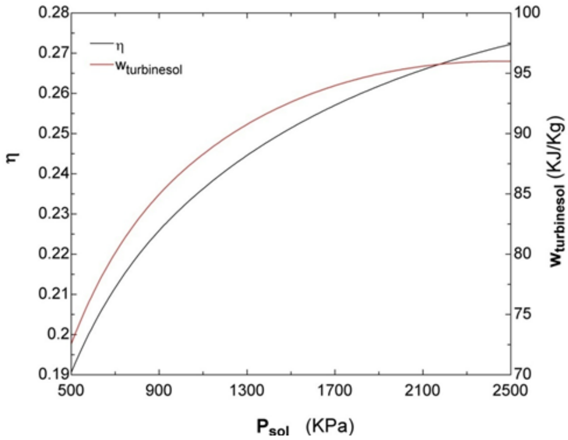

Figure 3. high side pressure versus output work and efficiency

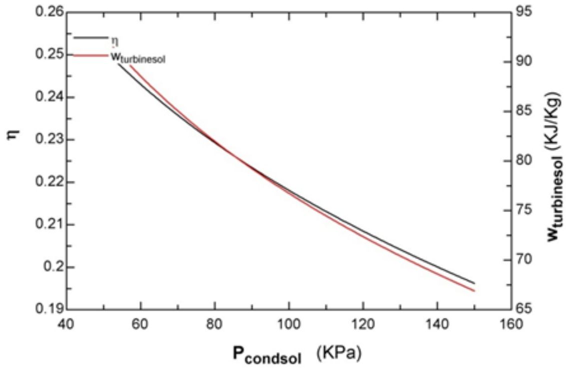

Figure 4. low side temperature versus output work and efficiency

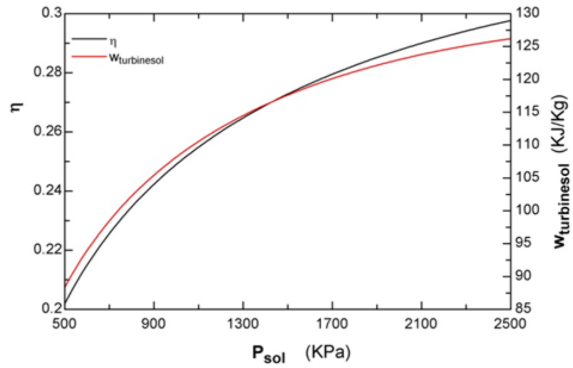

Figure 5(a). high side pressure versus output work and efficiency for medium temperature heat source.

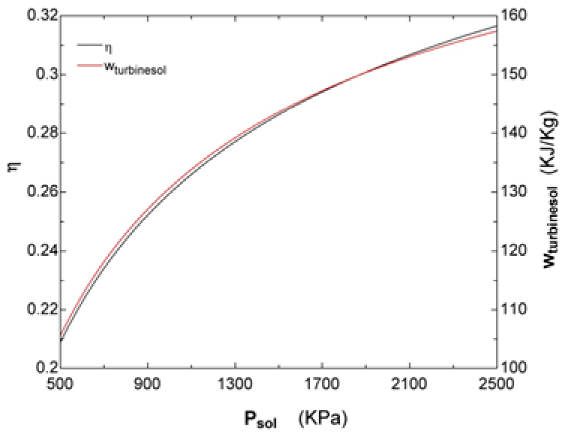

Figure 5(b).: high side pressure versus output work and efficiency for high temperature heat source.

The condenser pressure effect was studied on efficiency and work output. As it is seen in figures (6a) and (6b), the boiler pressure is kept constant while the turbine inlet temperature for medium and high ranges was taken at 120 °C and 180 °C respectively. The relationship resembles previous graphs; since it shows inverse relationship between condenser pressure and efficiency. This agrees with the previous results, which means as the condenser pressure increases, the pressure difference across the expander inlet and outlet decreases. This results in decreased efficiency and work output.

After the preliminary process has been conducted, four fluids have been selected. These fluids have also fulfilled the safety and environmental specifications set by ASHRAE. These four fluids will be deeply analysed. Additional parameters will be taken into account which seems to be important in the performance of the system under study.

These fluids are:

1. R600 (N-Butane)
2. R290 (Propane)
3. R32 (Difluoromethane)
4. R410a (Puron)

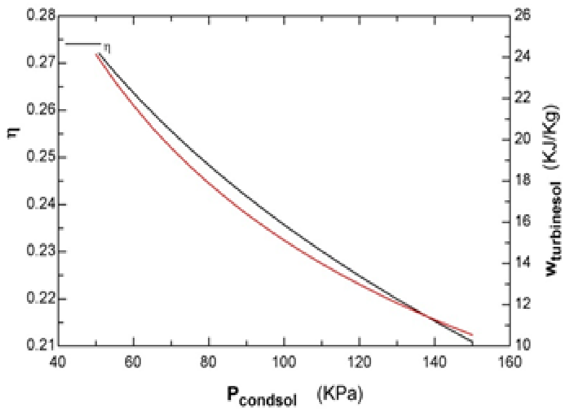

Figure 6(a). low side pressure versus output work and efficiency for high temperature heat source.

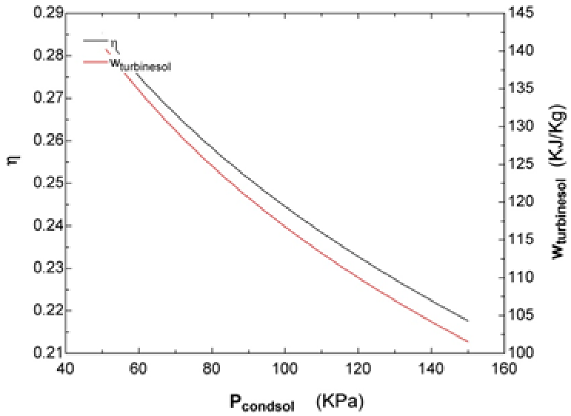

Figure 6(b). Low side pressure versus output work and efficiency for high temperature heat source

Table 2. Summary of the efficiency and output work for the sixteen fluids under different temperature heat sources.

Fluid	Efficiency %			Work (kJ/kg)		
	Low	Mid	High	Low	Mid	High
Ethanol	0.45	10	20.5	6.5	22	70
N-butane	14	16.5	24	13.5	50	164
methanol	2	10.5	18.5	7	30	60
R12	24	29.3	31	20	75	95
R22	27.5	29	32	75	102	127
R32	28	30	31	127	160	180
R114	12.5	24	25	7.5	65	70
R134a	23	27	28	65	95	115
R290	27	30	31	160	215	160
R407c	26.5	28.5	30	83	110	137
R410a	27	29.5	32	95	125	155
R502	27	30	31	62	85	108
R600	14	27	27	50	155	210
R600a	14	27	27	50	157	210
RC318	20	21	21	very low	49	85
water	very low	5	13	2.5	11	60

3. Detailed Analysis for the selected Fluids

R600 (N-Butane)

The first organic working fluid that was explored is the refrigerant R600 which is also known as n-butane. The T-s diagram of the fluid with pressure lines at 12.7, 150, 7600, 2500, and 4000 kPa is shown in Figure (7). The key feature that made R600 attractive is its low boiling points under reasonable pressure. This fluid has an inward slope for the T-S diagram in the gaseous side. This will ensure that the isentropic expansion process will have a 100 % vapour quality.

The first parameter considered was the effect of turbine inlet temperature. Figure (8) shows the effect of rising the temperature on pressure ratio of the turbine and the overall efficiency of the system. Figure (8) also shows that as the high side temperature continues to increase, the rate at which system efficiency grows trends to slow down.

Figure (8) shows the advantage of increasing the inlet temperature of the turbine. When the inlet temperature is increased, the pressure will also increase as shown in Figure (9). Unfortunately, this requires expensive turbine design.

The next parameter of the basic Rankine cycle that was investigated is the cold side temperature of the system. The high side temperature can be controlled better by varying the time of the fluid exposure to the heat source. The low side temperature is heavily dependent on ambient conditions. Figures (10) and (11) shows the importance of keeping the cold side of the cycle as low as possible to improve the performance.

Both the overall efficiency and net work produced by the expander decrease linearly as the low side temperature increases. The only benefit for having a heat sink at a higher temperature is the decreased expander ratio as shown in Figure (12). This added benefit of a lower pressure ratio only keeps the manufacturing process of the expander simple, but this also will affect the overall system negatively.

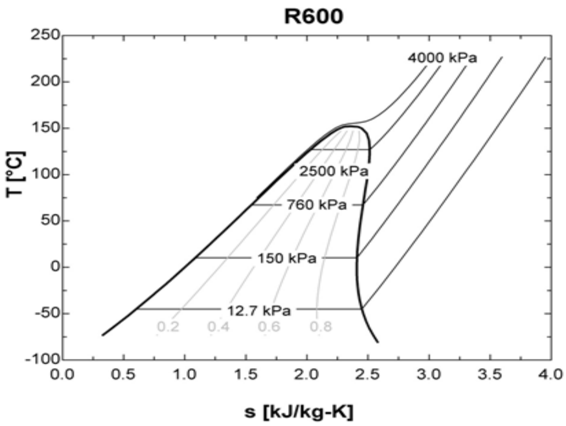

Figure 7. temperature entropy diagram

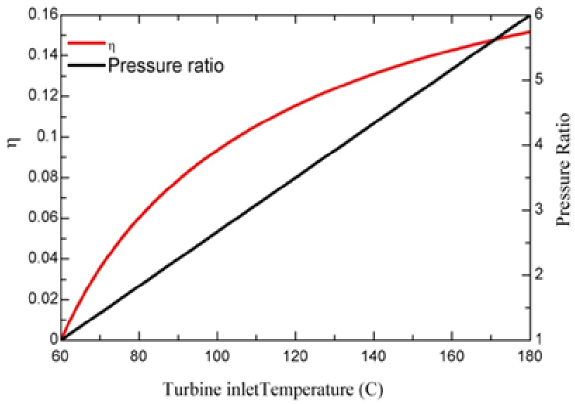

Figure 8. Effect of Expander Inlet Temperature on Pressure Ratio and Efficiency with Fixed Cold Side Temperature

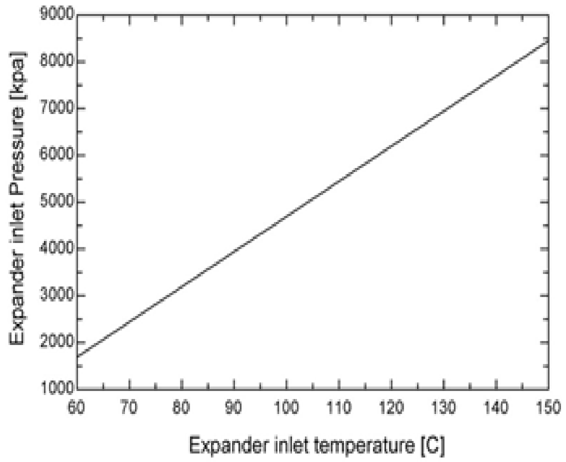

Figure 9. Effect of Expander Inlet Temperature on Inlet Pressure with Fixed Cold Side Temperature

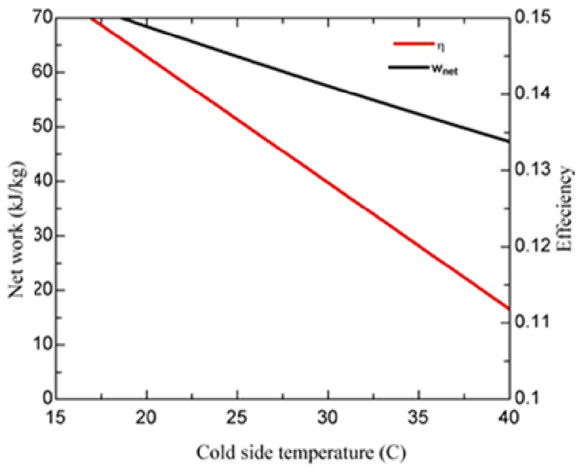

Figure 10. Effects of Cold Side Temperature on System Efficiency and Net Work

The last input of the basic Rankine Cycle to be studied is the boiler pressure. Figure (13) shows that there was a set pressure ratio of five for the expander. The input pressure was varied from 1300 to 2000 kPa to keep within the original system parameters set. The figure shows that for a fixed pressure ratio with the states pinned to the vapor dome, the inlet pressure has an almost negligible effect on the net work and efficiency of the cycle. Figure (13) shows that the relation between the inlet pressure and the expander pressure is linear. There is also an exponential relationship between the inlet pressure and the efficiency of the cycle. The figure demonstrates that the most influential factor on the simple Rankine cycle is the expander ratio.

The same parametric analysis has been done for the fluids: R32, R290, and R410a. The obtained results are summarized in Table 3.

As table (3) shows; three of the fluids have an acceptable condensing temperature that agrees with design ambient temperature. The fluid of maximum efficiency and work is R290 with values of 12.3% and 55 kJ/kg. Its safety group is A3 which means that it is a highly flammable fluid .Thus R600 becomes the first option for design consideration. As it can be seen from table (3) it has an efficiency of 11.5% and a net work of 52 kJ/kg. The use of this fluid will affect the initial cost of the turbine due to high pressure ratio.

4. Thermodynamic Analysis

It was found that R600 is the most suitable fluid for Organic Rankine Cycle, so first it will be analysed using geothermal source as main heat source for the cycle. Based on the results obtained, further optimization will be decided.

4.1. Geothermal Rankine Cycle

The geothermal Rankine cycle is presented in Figure 14. EES and CHEMCAD software are used to analyse this cycle. Table 4 shows the assumptions used.

Table 4. Assumptions made for calculations

Turbine Isentropic Efficiency	85 %
Pump Isentropic Efficiency	85 %
Heat Exchanger Efficiency	85 %
Geothermal water inlet temperature (C^0)	60

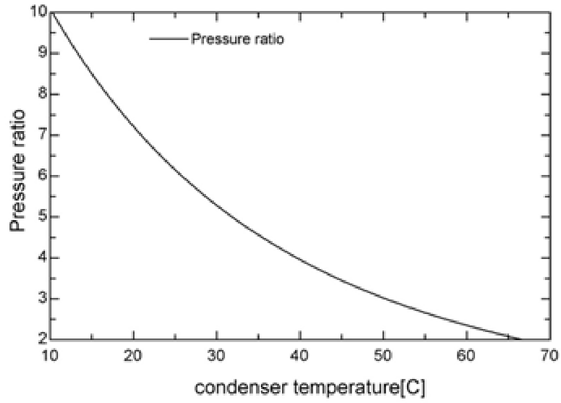

Figure 11. Relationship between Pressure Ratio and Cold Side Temperature

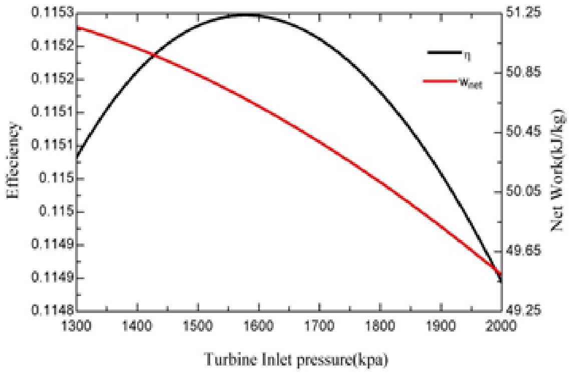

Figure 12. Effects of Expander Inlet Pressure on Efficiency and Net Work with Fixed Pressure Ratio

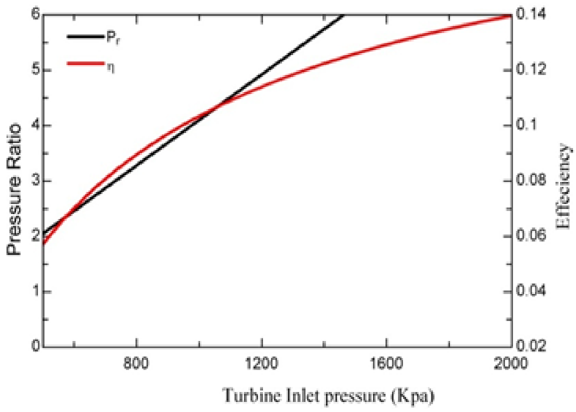

Figure 13. Effects of Expander Inlet Pressure on Efficiency and Pressure Ratio with Fixed Cold Side Temperature

Table 3. Summary for the main design parameters

Fluid	Expander inlet pressure (kPa)	Expander outlet pressure (kPa)	Pressure ratio	Hot Side Temperature (°C)	Cold Side Temperature (°C)	Net Work Output kJ/kg	Optimum Efficiency %
R600	1450	250	6	60	25	52	11.5
R32	1600	800	2	60	24	42	11.3
R290	1550	775	2	60	26	55	12.3
R410a	1600	800	2	60	0	30	11

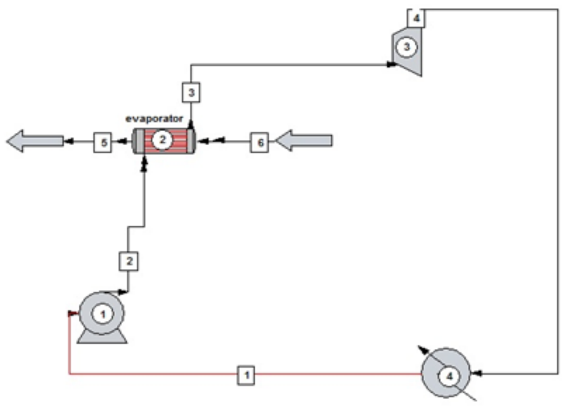

Figure 14. Simple Geothermal Rankine Cycle

4.2. Results and Observations

The results obtained using EEs and CHEMCAD software are given in tables (5) and (6):

Table 5. Streams Characteristics

Stream No.	Temperature using EES (C^0)	Temperature using Chemcad (C^0)	Pressure (KPa)
1	21.75	21.75	220
2	21.78	21.8	300
3	54.27	55	300
4	45.47	47.47	220

Table 6. Geothermal Rankine cycle Performance Characteristics

Quantity in question	Results using EES	Results using Chemcad
Turbine work (kJ/kg)	11.45	11.5
Pump work (kJ/kg)	0.14	0.16
Net work(kJ/kg)	11.31	11.34
Heat input (kJ/kg)	420.70	429.3
Heat output (kJ/kg)	409.40	417.9
Efficiency	2.70 %	2.64 %

A small difference between EES and CHEMCAD results is seen. This can be understood, since EES is more theoretically aligned and gives idealized results, while CHEMCAD simulates results that are close to the actual case; however some idealizations are assumed too.

The results show a low efficiency and work output which is expected due to the low pressure difference across the expander. This is attributed to two reasons, first one is restriction on the evaporator side temperature that is connected to the geothermal water temperature which is capped at 60 °C, and the second one is the condenser temperature, which should be close to the ambient temperature so condenser load is not too high.

It can be concluded that geothermal sources are not enough to generate power in Jordan. In order to increase the efficiency and the work output, the evaporator side temperature must be increased and the condenser side temperature must be lowered. However the condenser temperature is constrained by ambient temperature which (unfortunately) cannot be controlled, so the evaporator side temperature must be increased. However it is constrained by the geothermal side temperature which is topped at 60 °C, so another heat source is needed to be added, this source is solar energy, which is found in abundance in Jordan.

Combined Rankine Cycle

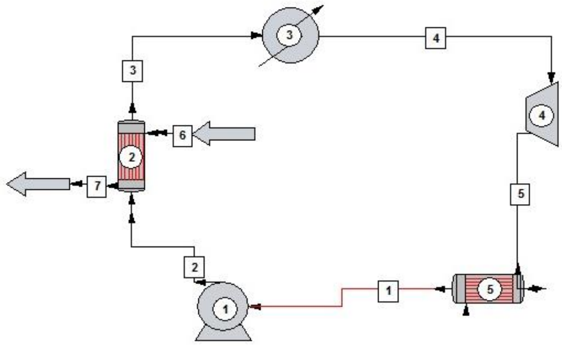

Figure 15. Simple Solar and Geothermal Rankine cycle

A basic Rankine cycle is used here with two heat sources, geothermal water is used as pre heater and solar collector is used as the primary heat source. In figure (15) solar panel is modelled as a boiler with an output temperature of 150 °C. Stream (2) is preheated using geothermal heat exchanger (2). After that stream (3) is passed through solar collector (3) to be evaporated and superheated. The superheated vapor (4) is passed through the expander (4) and its pressure is reduced to the condenser pressure, which must be selected so that condensation temperature doesn't fall below 20 °C. The wet mixture (5) is condensed to saturated liquid (1) in the condenser (5), and then stream (1) is pumped back to the boiler pressure and the cycle starts again.

The Evaporator side pressure is selected to ensure superheating the expander inlet stream, so the expander can be used efficiently with no vapor entering. Also it will be limited by the turbine design. Since we have a solar collector with temperature output of 150 °C the selected pressure is 3500 kPa, which meets the above criteria and will be used in the following cycles as the evaporator pressure. On the other hand, the condenser pressure is selected to ensure that condenser temperature doesn't fall below 20 °C Going below 20 °C requires more energy to be removed which will affect the overall efficiency of the cycle. In the case of R600, it will be 220 kPa, where this pressure will be used in the following cycles as the condenser pressure.

A further modification to the solar and geothermal Rankine cycle was applied and their effect on efficiency and work output was observed. These modifications are using regeneration techniques in the form of open feed heater and closed feed heater.

Open feed heater Solar and Geothermal Rankine cycle alternative was investigated, which showed a small improvement in the efficiency with a small decrease in work output, of 19.1 % and 84.6 KJ/Kg respectively. This behavior is expected since some of the turbine steam is extracted in order to reheat the geothermal heat exchanger inlet, which resulted in the increased efficiency.

Closed feed water heater solar and geothermal Rankine cycle was the next alternative to be studied, which showed a slight improvement from the open feed heater cycle in efficiency and work output of 20 % and 85 KJ/Kg respectively. This means that the open cycle is more feasible than this one, since it has one less component which is the closed feed heater exchanger.

Finally, using both types of regeneration and reheating between turbine stages in a cycle was investigated to its effect on efficiency and work output, surprisingly the efficiency and work output decreased from the previous cycles, where its values is 18% and 86 KJ/Kg respectively, which rendered this cycle infeasible due to its complexity and low return.

5. Conclusions

During the process of exploring different working fluids, a preliminary selection between 16 fluids was conducted. Work and efficiency are considered as key output parameters while the high side pressure, low side pressure and source temperature parameters were the varying ones. A typical behavior resulted for most of the fluids when increasing the temperature and the pressure of high side of the system. The work and efficiency revealed an improvement during that process while they suffered an exponential decrease in their magnitudes as the condenser pressure increases.

Each fluid demonstrated positive result in a given range. For the low temperature range the fluids R22, R32, R134a, R407c, R410a and R502 have show a good efficiency (approximately 27%) and work output. While in the mid range fluids R12, R22, R32, R290, R410a and R502 showed a higher efficiency (approximately 30%) and better work output. Finally in the high temperature range the fluids R12, R22, R32, R290, R410a, R502 and R600 had a slight improvement from the previous range in efficiency of approximately 31% and some fluids showed a good jump in work output.

From the previous fluids, four ones were selected based on their efficiency and power output in the different ranges, these fluids are: R600, R32, R290 and R410a.Those fluids showed very promising results at all ranges of temperature. R600 was found to be the most suitable fluid for our application.

The potential for using geothermal Rankine cycle for power generation in Jordan was studied, taking into accounts geothermal water temperature, its flow rate and the ambient temperature. It was found that this kind of cycle will have low efficiency of 2.7% and power output of 11.34 kJ/kg for geothermal springs in Jordan. This was the result of low geothermal water temperature ($60C^0$) and high ambient temperature which will require a huge amount of heat to be ejected in the condenser. This value is very low in all standards and not feasible to be constructed.

To improve the overall efficiency and power output, a combined solar geothermal cycle was tested. It was found that open feed water heater solar geothermal organic Rankine cycle is the most efficient cycle for power generation in Jordan.

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