ENERGY AND EXERGY ANALYSIS OF A GEOTHERMAL POWER STATION WITH TWO-PHASE CLOSED THERMOSYPHON SYSTEM IN AN ORGANIC RANKINE CYCLE

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ABSTRACT

In this paper, an enhanced FORTRAN code was combined with the EES software to develop thermodynamic model and exergy analysis of a two-phase closed thermosyphon system to generation electricity in an organic rankine cycle (ORC). Working fluids considered are R134a, R123, R22, Water, and ammonia. Energy balance is carried out to predict operating conditions of the process. Output of energy balance are used as input for exergy analysis and components of ORC. We also calculated the extraction rate for different lengths of evaporator heat pipe and different temperatures of the geothermal temperature range of 50-200℃. Finally the energy, Exergy distruction ratio and network output for different working fluids is comparable.

KEYWORDS: *Geothermal power plant, two-phase closed thermosyphon, Exergy, ORC.*

I. INTRODUCTION

Geothermal energy is going to be an attractive energy source due to rising oil prices and environmental pollution concerns. Since the price of oil has reached its peak and efforts are necessary to find alternative energy resources, geothermal energy is more competitive when compared to conventional fossil fuel systems and direct use of geothermal energy has increased approximately twofold in the last five years [1]. Geothermal energy is used to generate electricity and for direct uses such as space heating and cooling, industrial processes, and greenhouse heating. High-temperature geothermal resources above 150°C are generally used for power generation. Moderate temperature (between 90 and 150°C) and lower-temperature (below 90°C) geothermal resources are best suited for directuses [2]. Exergy analysis is vital in designing, optimizing and modeling these kinds of cycles. Exergy analysis is now a mature methodology that accounts for the system's inefficiency in terms of exergy destruction, i.e., the degradation of the system's ability to perform work with respect to its surroundings[3].The Two-Phase Closed Thermosyphons (TPCTs) are the high-performance heat transfer apparatuses, which are used to transfer a large amount of heat at a high rate with a small temperature difference. They are widely used because of their simple structure when compared with other types of heat pipes [4]. To utilise low enthalpy natural heat sources, a TPCT using a binary fluid is a good device, which can extract heat without using electric power. For example, when the heat flux in a geothermal bore is moderate, then it is a convenient way to use a long TPCT device [5]. Zuo and Faghri (1998) summarised a 'network' model of the heat pipe operation. The network model provided a simple way to calculate temperatures and heat fluxes in the heat pipe. However, the working fluid vapour and thus the working-fluid-related operating limitations could not be examined by this model. Therefore, they proposed a thermodynamic cycle analogy to the heat pipe operation [6].In this paper, combination of the exergy analysis and the lumped capacity was used to simulate thermal characteristics of a long TPCT system. The aims of this paper are as follows:

1. The exergy analysis of the two-phase closed thermosyphon system was performed for some refrigerants as the working fluids in an ORC.
2. Predict extracted heat as a function of the length of evaporator heat pipe based on different working fluids.
3. Comparing different working fluids at different operating condition such as: First and second thermodynamic law, Exergy distruction ratio,..

II. ANALYSIS OF A (TPCTS) AND (ORC)

As shown in Fig. 2, the two-phase closed thermosyphon is a closed container filled with a small amount of working fluid. According to this figure, heat is added to the evaporator wall, which causes the liquid in the pool to evaporate. The generated vapor then moves upwards to the condenser. The heat transported is then rejected into the heat sink by a condensation process. The condensate forms a liquid film which flows downwards due to gravity. Here, the heat flux rate (Q_e) and the convective cooling conditions (h_∞ and T_∞) are given.

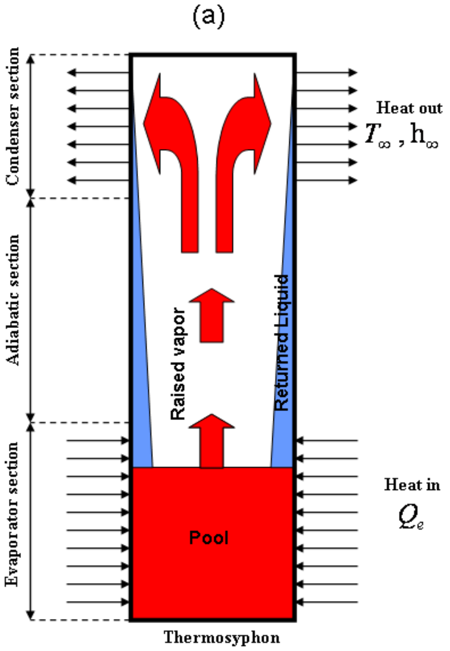


Fig 1. Schematic drawing of the TPCT operation

2.1. Organic Rankine Cycle (ORC) with a two-phase closed thermosyphon

The cycle considered is a simple cycle, which consists of a pump, heat exchanger, turbine and condenser (Fig. 1). The working fluid is saturated liquid at the exit of the condenser; it is then pumped to the heat exchanger where it gains heat from the heat source. Hot pressurized working fluid expands in the turbine thereby doing useful work. Pump and turbine efficiency is 80% and generator efficiency is 90%. The turbine efficiency is assumed to be the same for all working fluids and all cases considered. The selection of the working fluid has great implications for the performance of a binary plant. While there are many choices available for working fluids, there are also many constraints on that selection that relate to the thermodynamic properties of the fluids as well as considerations of health, safety, and environmental impact [7]. This work investigates the potential of different working fluids for power production at different operating pressure for subcritical cycle. Energy and exergy balance of the cycle is carried out. The investment cost of low-temperature energy recovery system (power cycle) is highly dependent on the cost of the components, i.e. heat exchangers, turbine, pumps and pipes. The cost of these components is directly related to size. Therefore it is important to compare the size of the components needed for different working fluids.

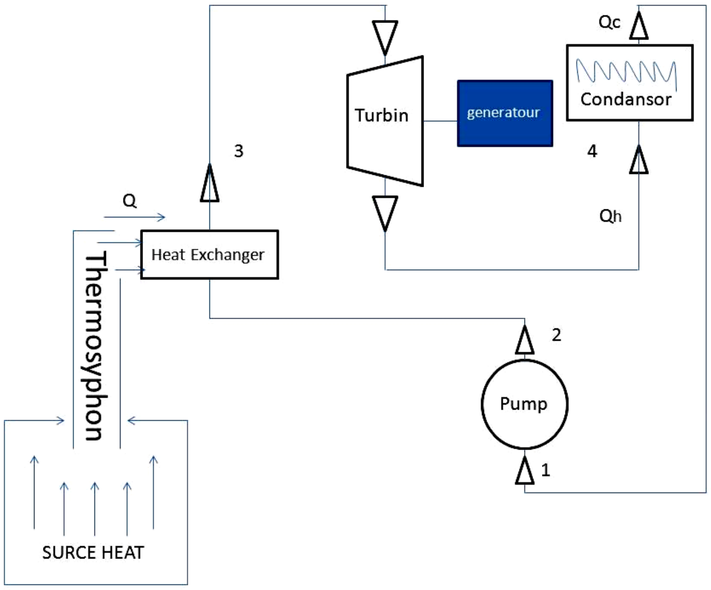


Fig 2. schematic of a geothermal power plant with a two-phase closed thermosyphon

III. ANALYSIS

3.1. Energy and exergy analysis

The solution to energy and exergy determines the mass flw rate of the working fluis, temperature and pressure at each point. Air mass flow rate of 25 kg/s is used for all cases and the other parameters used in the simulation shows in Table 1. The equations are solved using engineering equation solver, EES. EES has built-in thermodynamic and transport property function for different working fluids.

Table 1: Parameters used in the simulation

Parameters	Value
T_0 [℃]	25
T_{geo} [℃]	150
η_T [%]	80
η_P [%]	90
P_3 [kpa]	1200
P_4 [kpa]	140
$\dot{m}_{air}$ [kg/s]	25

The following assumptions are considered during this study:
a) The geothermal power plants operate in a steady-state condition.
b) The pressure drops throughout the heat exchangers and pipelines are neglected.
c) The turbines and pumps have isentropic efficiencies.
d) The kinetic and potential energy changes are negligible.
e) The geofluid is in a saturated liquid condition in the reservoir (x = 0).
f) Fresh water properties have been used in the analysis instead of the thermodynamic properties of the geofluid.
g) Temperature and pressure losses of the geofluid are neglected in the separation and condensation processes.
h) The flashing process is accomplished at constant enthalpy.

Mass, energy and exergy balances for any control volume at steady state with negligible kinetic and potential energy changes can be expressed, respectively, by

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{2}$$

$$\dot{E}_{heat} - \dot{W} = \sum \dot{E}_{out} - \sum \dot{E}_{in} + \sum \dot{E}_{D} \tag{3}$$

where $\dot{Q}$ and $\dot{W}$ are the net heat input and work output, $\dot{m}$ is the mass flow rate of the fluid, h is the enthalpy, the subscripts in and out stand for inlet and exit, $\dot{E}_D$ is the rate of exergy destruction, and $\dot{E}_{heat}$ is the net exergy transfer by heat at temperature T, which is given by

$$\dot{E}_{heat} = \sum \left(1 - \frac{T_0}{T}\right)\dot{Q} \tag{4}$$

where T is the temperature at which heat transfer takes place. The specific flow exergy and the rate of total exergy are given by

$$e = h - h_0 - T_0(s - s_0) \tag{5}$$

$$\dot{E} = \dot{m}e \tag{6}$$

where the subscript 0 stands for the restricted dead state and T0 is the dead state temperature. The energy and exergy efficiencies are generally defined as

$$\eta_{\mathrm{I}} = \left(\frac{\text{energy in products}}{\text{total energy inputs}}\right) \tag{7}$$

$$\eta_{\mathrm{II}} = \left(\frac{\text{energy in products}}{\text{total energy inputs}}\right)$$

(8)

3.2. Performance evaluation

In general, the first-law efficiency of a geothermal power plant may be expressed as [7].

$$\eta_{I,1} = \frac{\dot{W}_{net}}{\dot{m}_{geo}\left(h_{geo} - h_o\right)} \tag{9}$$

Net power

$$W_{net,orc} = W_{T,orc} - W_{P,orc} \tag{10}$$

The first-law efficiency may be expressed based on the heat transfer to the ORC

$$\eta_{I,1} = \frac{\dot{W}_{net,orc}}{Q_{in,orc}} \tag{11}$$

Using the exergy of geothermal water as the exergy input to the plant, the second-law efficiency of a geothermal power plant can be defined as [7].

$$\eta_{II,1} = \frac{\dot{W}_{net,orc}}{\dot{E}_{in}} = \frac{\dot{W}_{net,orc}}{\dot{m}_{orc}[(h_3 - h_2) - T_0(s_3 - s_2)]} \tag{12}$$

The total exergy destruction rate in the cycle is determined from

$$\dot{E}_D = \dot{E}_{D,P} + \dot{E}_{D,E} + \dot{E}_{D,T} + \dot{E}_{D,C} + \dot{E}_{D,CA} \tag{13}$$

For the sake of comparison, it is better to use the exergy destruction ratio, $Y_{D,i}$, which is the exergy destruction rate in a component compared to the exergy rate of the fuel provided to the overall system [8]. Thus,

$$Y_{D,i} = \frac{\dot{E}_{D,i}}{\dot{E}_{in}} \tag{14}$$

where, $\dot{E}_{in}$ in is the exergy of geofluid.

3.3. Energetic and exergetic relations for the subsystems of the (ORC) geothermal power plant

Pump		
Energy relations	$h_p = \frac{h_{s,2} - h_1}{h_2 - h_1}$	$w_{P,orc} = \dot{m}_{orc}.(h_2 - h_1)$
Exergy relations	$\dot{E}_P = T_0.\dot{m}_{orc}.(s_2 - s_1)$	$Y_{d,P} = \frac{\dot{E}_P}{Q_{in,orc}}$
Turbine		
Energy relations	$h_p = \frac{h_3 - h_4}{h_3 - h_{s,4}}$	$w_{T,orc} = \dot{m}_{orc}.(h_3 - h_4)$
Exergy relations	$\dot{E}_T = T_0.\dot{m}_{orc}.(s_4 - s_3)$	$Y_{d,T} = \frac{\dot{E}_T}{Q_{in,orc}}$
Condenser		
Exergy relations	$\dot{E}_C = T_0.\dot{m}_{orc}.(s_1 - s_4)$	$Y_{d,C} = \frac{\dot{E}_C}{Q_{in,orc}}$

Overall energy balance in the condenser

$$\dot{m}_{orc}.(h_4 - h_1) = \dot{m}_{air}(h_6 - h_5) \tag{15}$$

IV. RESULTS AND DISCUSSION

In order to validate the present combination models, some test were conducted based on the data available in Kusaba[5]. The lines in the Figure 3,4,5,6, comparison of the extracted heat as a function of saturated temperature geothermal of the present model for different working fluids with the kusab results [5]. As shown in figures [3,..,6], is a linear relationship between extracted heat and saturated temperature geothermal. In order to test with the different working fluids, we used the EES software within FORTRAN code. According to figure [7,...,10] comparison of the extracted heat as a function of the length of TPCT for different working fluids. In figures [7,..,10] the predicted performance is shown for geothermal temperature of 100 and 150 °C according to length of TPCT by using R22, R143a, water and Ammonia as working fluid. Figure. 12 shows depicts the exergy destruction ratio in each components of the geothermal ORC for different working fluids. The maximum distruction ratio is related to condenser for R22(51.53%), R134a(18.93 %), water(12.06%), R123(4.0.4%), respectively. The next-largest exergy destruction occurs in the cooling air, turbine, respectively.

Figure 11. shows the resulted the net work out in an ORC for different working fluids. this figure the maximum network for water and the minimum network for R123.

The Table 2. shows Summary results for the first and second law efficiency and energy analysis of the ORC.

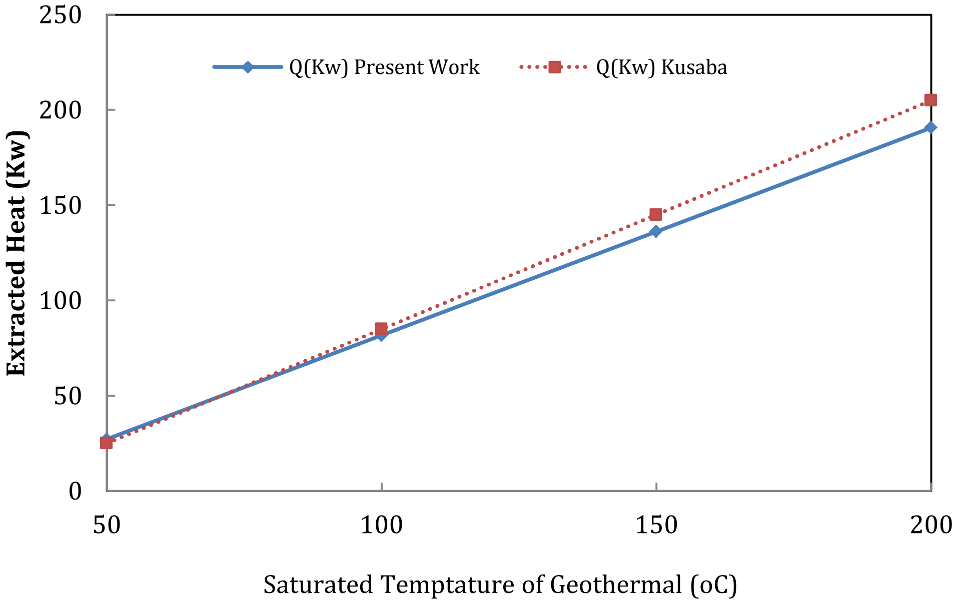


Figure 3: Ammonia Working Fluid in TPCT

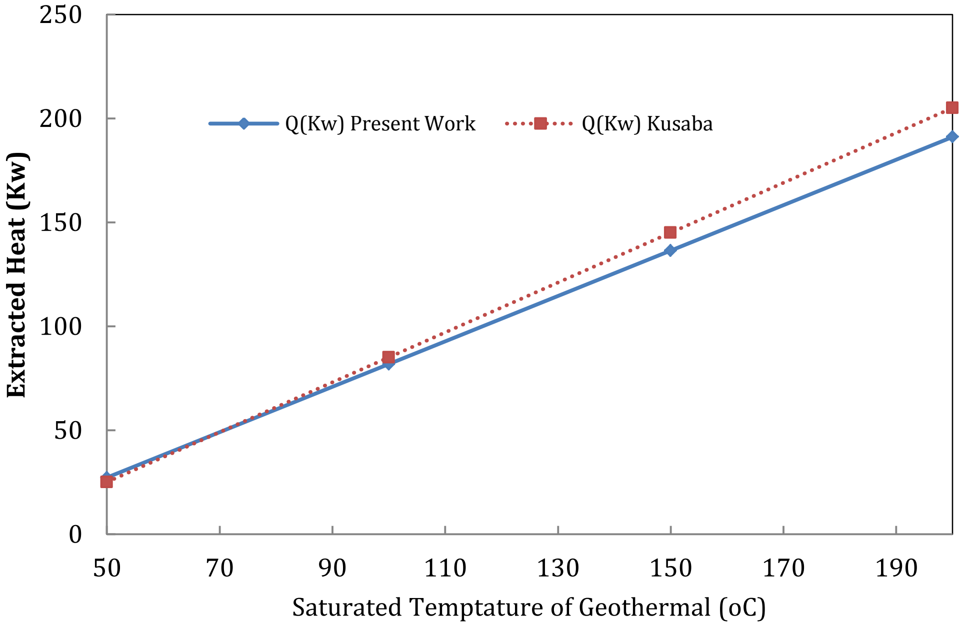


Figure 4: Water as working fluid in TPCT.

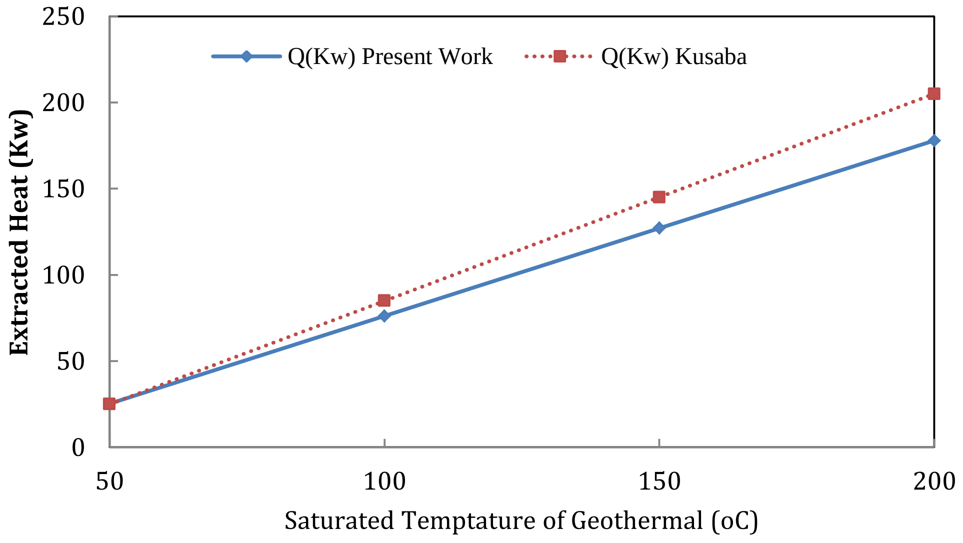


Figure 5: R22 as working fluid in TPCT.

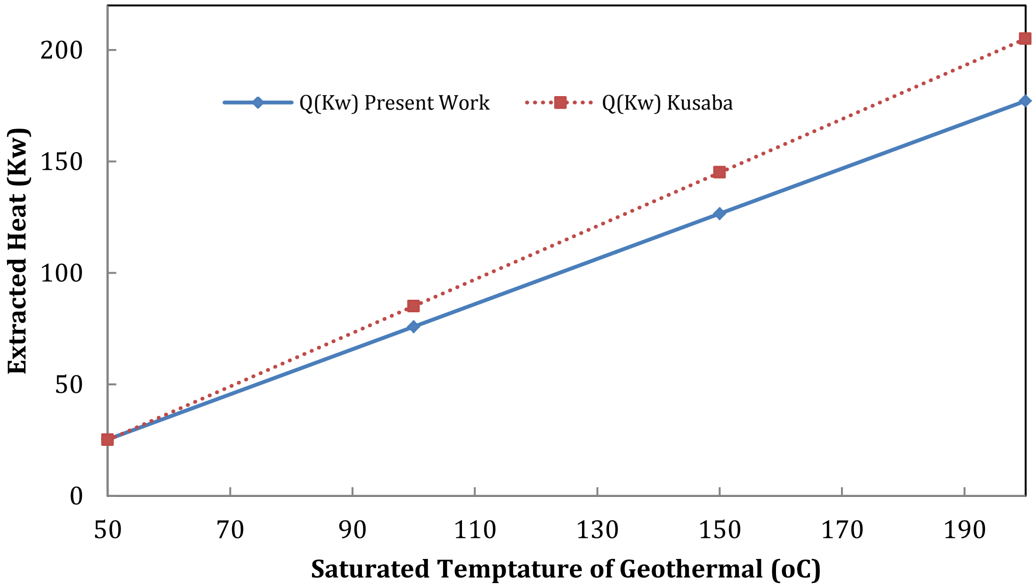


Figure 6: R134 as working fluid in TPCT.

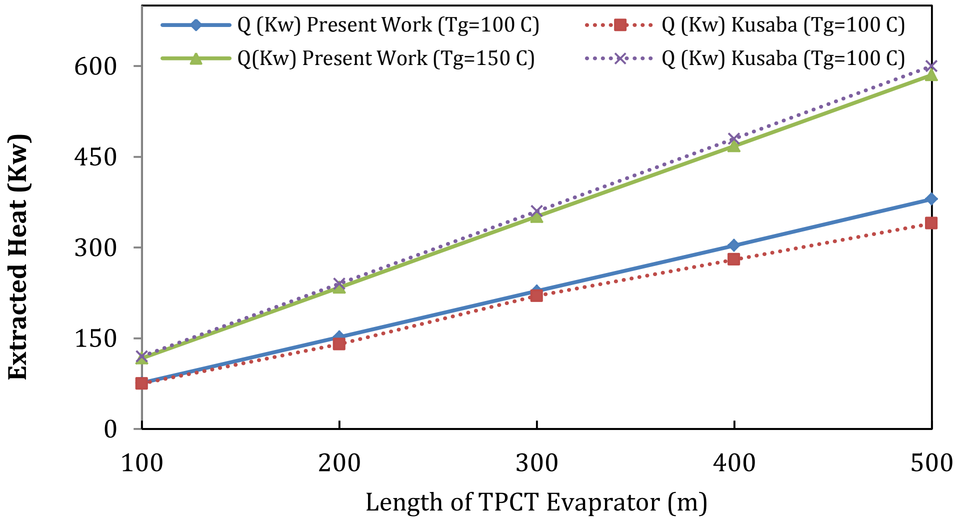


Figure 7: Extraction Heat as a function of the length of TPCT(Ammonia)

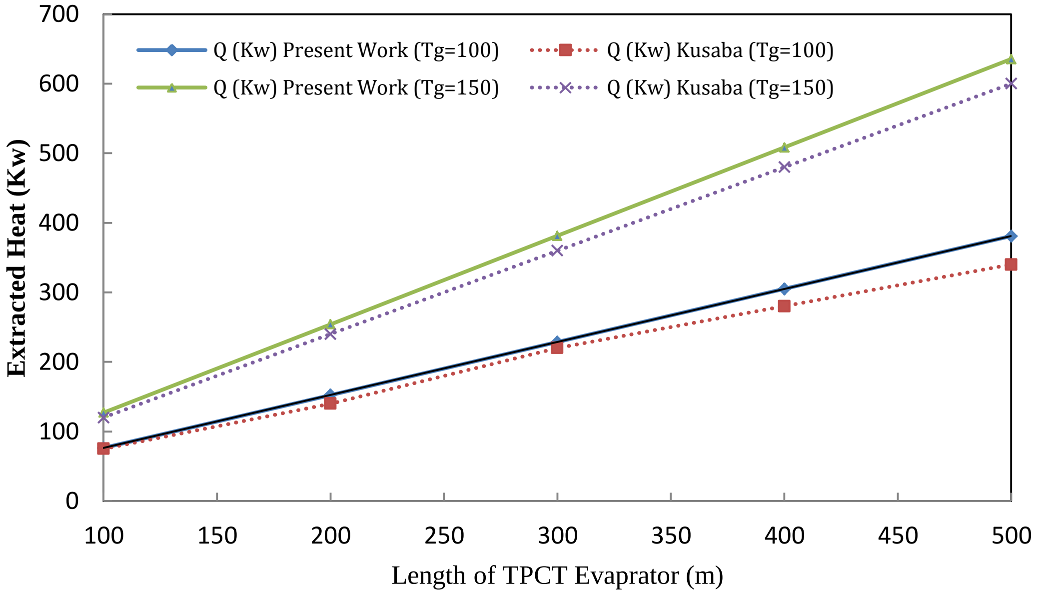


Figure 8: Extraction Heat as a function of the length of TPCT(R22)

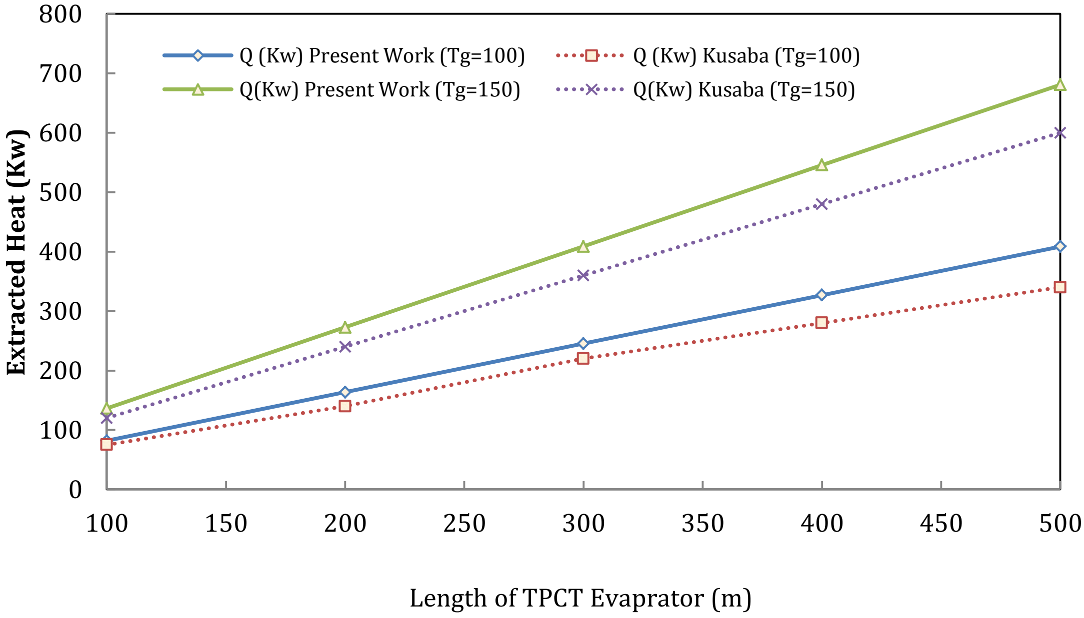


Figure 9: Extraction Heat as a function of the length of TPCT(Water)

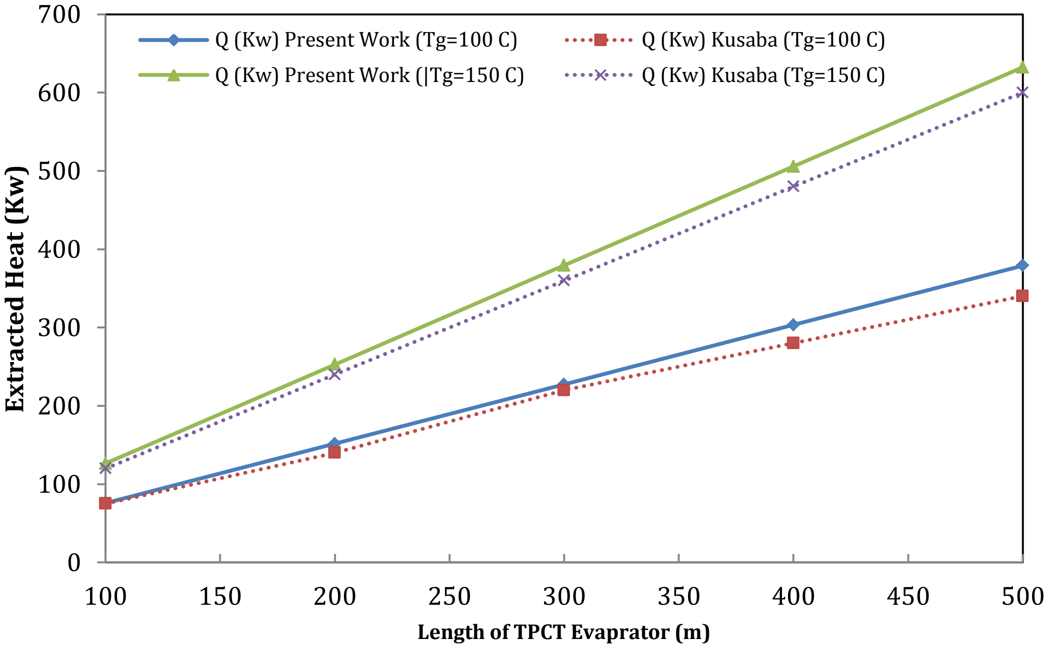


Figure 10: Extracted heat as a function of the length of TPCT (R134a)

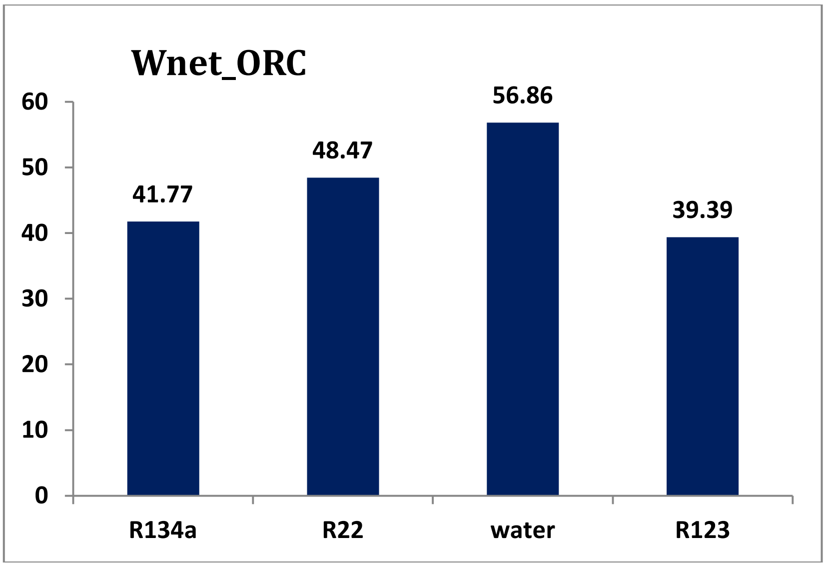
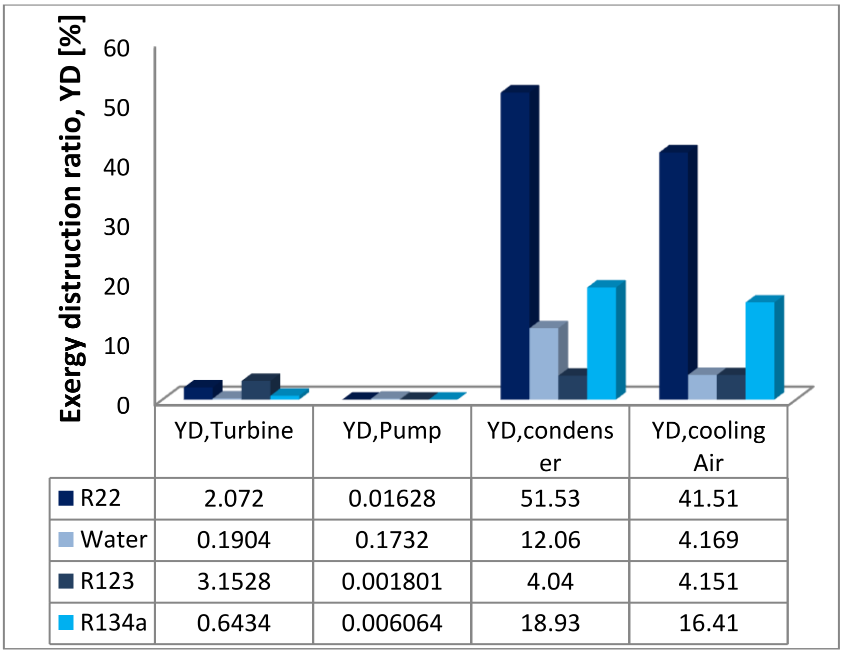


Figure 11: The net work out in an ORC for different working fluids



	YD,Turbine	YD,Pump	YD,condenser	YD,cooling Air
■ R22	2.072	0.01628	51.53	41.51
■ Water	0.1904	0.1732	12.06	4.169
■ R123	3.1528	0.001801	4.04	4.151
■ R134a	0.6434	0.006064	18.93	16.41

Figure 12: The rate of exergy destruction of the components of geothermal ORC

Table 2. Summary results for the first and second law efficiency and energy analysis of the ORC.

Performance Parameter	R22	R123	R134a	Water
$\dot{Q}_{in\text{-} ORC}$	127.1	142	126.1	136.4
$\eta_{1,ORC}$	33.37	27.74	33.13	41.69
$\eta_{2,ORC}$	20.51	14.23	15.6	12.54
$\dot{E}_C$	23.11	-20.2	-23.95	-16.45
$\dot{E}_T$	6.439	0.7642	23.13	0.2597
$\dot{E}_P$	2.532	0.0090	0.0076	-0.236
$\dot{E}_E$	14.14	19.43	0.8138	16.43
$\dot{E}_{CA}$	20.76	20.76	20.76	20.76

$\dot{E}_D$	20.76	20.76	20.76	20.76

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