



Geothermal Power Plants Applying Organic Rankine Cycle in Iran

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Abstract

With the rise of gas and oil prices to provide energy and the increase of environmental pollution, countries are trying to replace fossil fuels with renewable energy. There are various types of renewable energy. Geothermal energy is one of the independent energies of solar energy. Geothermal energy which has been stored in the earth for thousands of years from solar energy, as well as nuclear fissures which are originated in the depths of the Earth, are mainly concentrated in seismic and volcanic areas and the Earth's surface. The temperature in the Earth's core is more than 5000 degrees Celsius. The history of geothermal energy in Iran dates back to almost 50 years ago, when extensive research was started in this field. Researchers surveyed Sabalan, Damavand, Khoy, Mako and Sahand regions (Younes Noorollahi, Hossein Yousefi, 2010). Finally, three deep wells were excavated for exploration and two wells with a temperature of 240 ° C and a depth of 3197 meters were exploited. But the exploitation of geothermal energy is very costly. The major part of this cost is related to excavating wells, a great expense must be paid for excavating wells with a depth of more than 1000 meters. These expenses are generally not economically viable for Middle Eastern countries such as Iran, where cheap fossil fuels are costly and therefore the use of this energy is not very cherished in Iran.

Due to its geographical location, Iran is loaded with oil wells in the central and southern part of the country. Some of these wells can be harvested and some of them have expired. The purpose of this project is to generate electricity with the help of heat inside oil and gas wells and the Rankin cycle. The Rankin cycle is one of the most efficient thermodynamic cycles for electricity generation. In this project, according to the condition of the well, the cycle is to be simulated and the obtained results will be examined. The output of turbine power is equal to 1200 kW which it can support 1000 families electricity in the south of Iran.

Introduction

Due to the increasing need for energy in developing countries and the increase in pollution because of excessive consumption of fossil fuels, the use of renewable energy has become significant. Geothermal energy has received more attention due to its high capacity, generative power and variety in its application. For example, it is used for native and biological purposes in shallow depths where the temperature is between 20 and 60 degrees Celsius (Pisciculture, agriculture, home consumption, hot water, etc.) And at moderate depths, which have a temperature between 90 to 150 degrees Celsius, it is used for industrial purposes, and at greater depths with higher temperatures, it is used in power plants to generate power (Allahvirdizadeh, 2020). It is suggested that geothermal power plants that are proposed for power generation, use single and double stage instantaneous expansion steam for temperatures above 180 ° C and the organic Rankin cycle for lower temperatures. Most power bicycles require steam, which requires the fluid to be at a temperature of at least 130 degrees Celsius so that high-pressure steam can be used to generate electricity (Yari.M, 2010). But in many cases access to this temperature is difficult and costly. Therefore, the organic ranking cycle is used for temperatures below 120 ° C. The Rankin cycle uses an organic fluid that has a lower specific heat capacity.

Background and literature review

Organic Rankine Cycle:

The steam-assisted Rankine cycle is commonly used to generate electricity. In the Rankin cycle, the fluid must be converted to steam with the help of heat, so for environments where the temperature is less than 100 degrees, an organic fluid with a heat capacity less than water should be used. This cycle is called the Organic Rankine Cycle. The way the Organic Rankine Cycle operates is that in a pump, first the working fluid is compressed and then it is introduced into a heat exchanger until it is converted to steam. The turbine can generate electricity and then the steam enters a condenser with low pressure, with the help of the generated steam and this cycle continues this way. The ideal model of this cycle is that in this cycle the processes occur isentropic and isobaric. (Singh, O.K., Kaushik, S.C., 2013) That's mean, there is no heat transfer as the fluid passes through the turbine and pump, and the entropy remains unchanged. In this cycle, the working fluid in the evaporator and condenser also goes through a constant pressure process. But in the real cycle, irreversibility reduces the efficiency of the cycle. During fluid expansion, only part of the energy can be recovered through the pressure difference and converted into useful work, and the other part is lost through conversion to heat. The efficiency of an expander is determined by comparison with an isentropic expander.

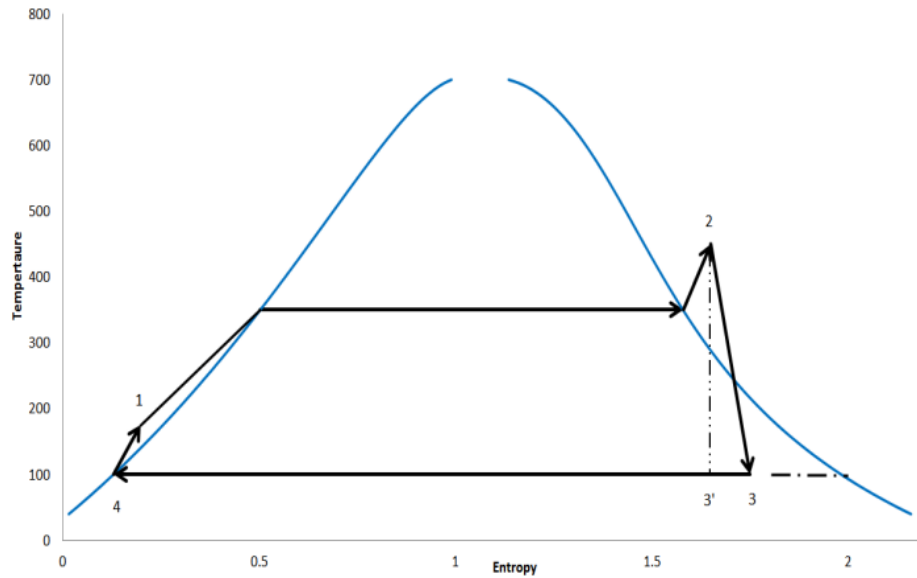


Figure 1: Rankine cycle diagram (Barse, Kirtipal, 2014)

Working fluid selection:

The choice of working fluid is very significant when the heat source is low in temperature. Due to the low temperature, the target fluid must be lower than the boiling point of water to reach the saturated and superheated point with less heat. For selecting a working fluid should be followed these guidelines (Babatunde, A. Fakeye, 2018, pp. 2-9):

- 1- Availability and low cost
- 2- Low ozone-depleting (ODP)
- 3- Low greenhouse warming potential (GWP)
- 4- High safety level: This parameter is involved flammability and toxicity.
- 5- Thermodynamic performance: The efficiency of the cycle and output power should be as high as possible.
- 6- Positive or isentropic saturation vapor curve: Organic fluid in the T-S diagram is divided into three types of fluid (dry with a positive slope, wet with a negative slope, and isentropic with a vertical slope). According to figure 2, during expansion in a turbine dry working fluid has not any liquid droplets, and this choice is due to avoid turbine damage. (Babatunde, A. Fakeye, 2018)
- 7- High vapor density: This parameter is important because low vapor density cause increasing volume flow. This affects the cost of the system because increasing volume flow needs a bigger heat exchanger.
- 8- Low viscosity: This has resulted in low friction losses and high heat transfer in a heat exchanger.
- 9- Positive condensing gauge pressure

- 10- High-temperature stability
- 11- High conductivity working fluid in a heat exchanger
- 12- The melting point should be lower than the lowest ambient air
- 13- Acceptable evaporating pressure: high-pressure evaporation needs more investment

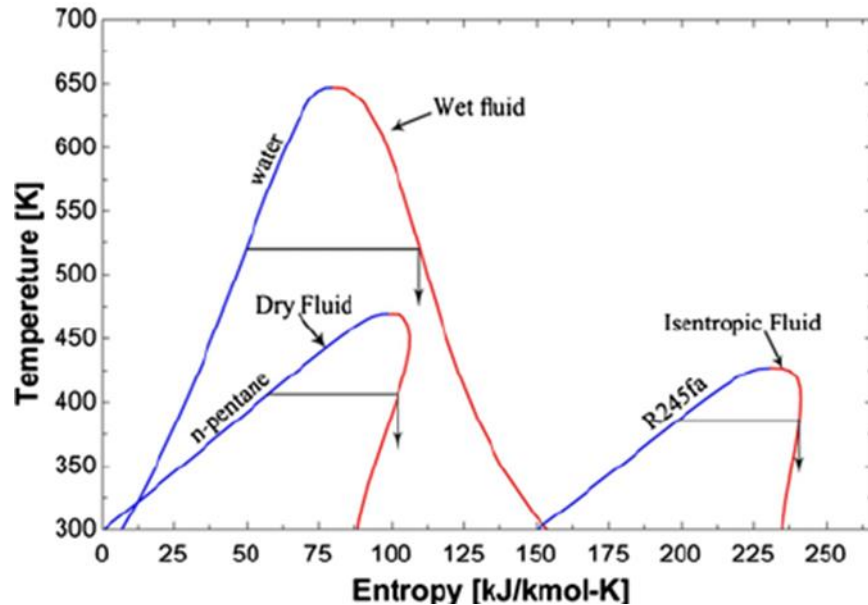


Figure 2: Types of working fluid

The entropy and temperature diagrams of the selected working fluids are plotted with the help of HYSYS and Excel. According to the diagrams and explanations, Iso-butane and n-pentane working fluids are more efficient in the Rankine cycle. Also, according to the researches done in the geothermal wells in Sabalan, the Iso-butane operating fluid is being used. In addition, normal pentane has been reported to be a highly efficient operating fluid in geothermal Rankine cycles. (مهران عبدالحی پور عدل, شهرام خلیل آریا, صمد جعفرمدار, 2020)

Iso-butane and n-pentane are an organic fluid which evaporate quickly and are also highly flammable. On the other hand, compared to other fluids such as R-142b and R-134a, these two fluids do less damage to the environment regard to the Global warming potential (GWP) and the Low ozone depleting (ODP).

The physical properties of Iso-butane and n-pentane are summarized in the table below.

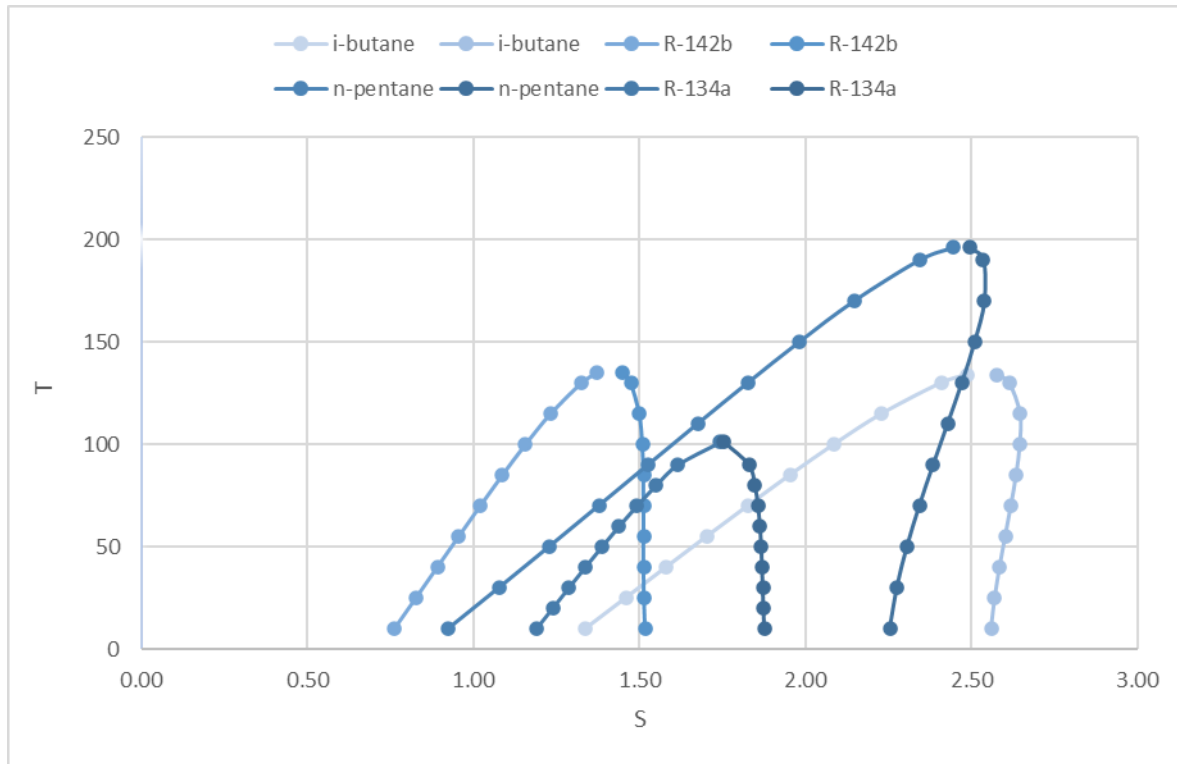


Figure 3: Comparing working fluid

Information about the terms of the project:

As mentioned, the exploitation of geothermal energy indirectly (i.e., the use of geothermal energy to generate electricity) is not very popular in most countries because it has a high cost. An important part of the cost includes the cost of drilling wells. Therefore, the aim of this project is to eliminate part of the drilling costs with the help of used oil and gas wells (Stáhl G, Pátzay G, Weiser L, Kálmán E., 2000). According to research conducted in this field, wells used with different characteristics are available in Iran. The research of this project has been done based on Fahlian oil fields. Fahlian oil fields are located in the south of Darkhovin (near Abadan). The depth of wells in this field is approximately from 2500 to 5000 meters.

The temperature in the core is more than 5000 degrees Celsius (میثم کلهری، ایمان خزایی، 1396). The earth's temperature increases nonlinearly due to its depth. The geothermal slope is believed to disappear after several tens of kilometres. But if in the initial depths, the increase in temperature in the earth's crust is considered linear, 3 degrees Celsius will be added for every 100 meters.

The heat transfer inside the evaporator (shell and tube heat exchanger) is highly dependent on factors such as hot fluid flowrate and hot fluid inlet temperature. The specifications of the pipes inside the well are considered the same as the pipes of the distribution network and water transmission lines. The size of the water transmission line pipes is 6 inches and the water speed in these pipes is close to 3 meters per second (Alina Żabnieńska-Góra, and Edyta Dudkiewicz, 2018). With the help of the pipe cross section and pipe speed, the volume flowrate to the heat exchanger can be obtained.

$$q \left(\frac{m^3}{s} \right) = V \left(\frac{m}{s} \right) * A(m^2) \quad (1)$$

Organic Rankin Cycle Modelling:

In the modelled Rankin cycle process with organic operating fluid, two models will be studied and analysed, and in the modelling process, an attempt is made to optimize the cycle performance based on the output power of the cycle.

In the first model, the schematic is of a simple Rankin cycle with an organic working fluid. Initially, hot water extracted from the ground enters the heat exchanger with high pressure and exchanges heat with the working fluid that has a lower boiling point and higher vapor pressure. In this way, the working fluid is completely evaporated along the converter pipes and getting in contact with hot water, it usually goes to the supersaturated area, and then enters the turbine to expand and generate power, then in an air-cooled condenser or water the coolant returns to the saturated liquid and thus completes the Rankine cycle (Klein, 2012). The fluid can be preheated with the working fluid before it enters the evaporator, if it is supersaturated when it exits the turbine. This reduces the heat received from the heat source and also increases the efficiency of the cycle. This process is the second simulated Rankine cycle model with an internal heat exchanger (Kanoglu, M., Bolatturk, A., 2008).

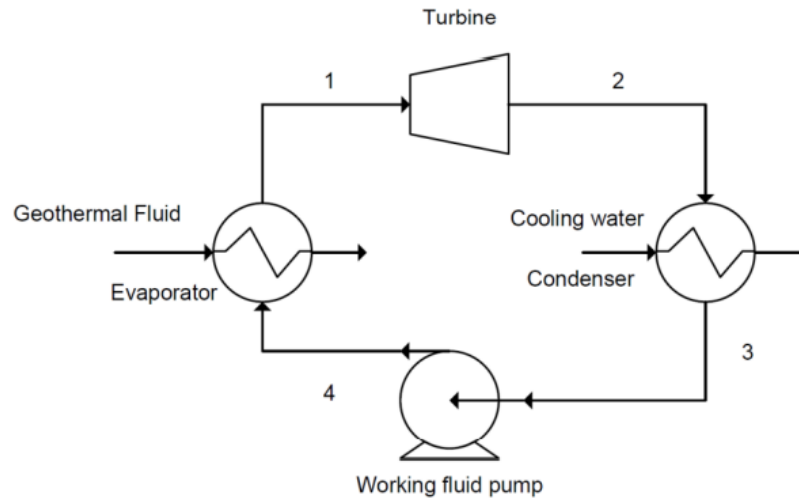


Figure 4: Rankine cycle

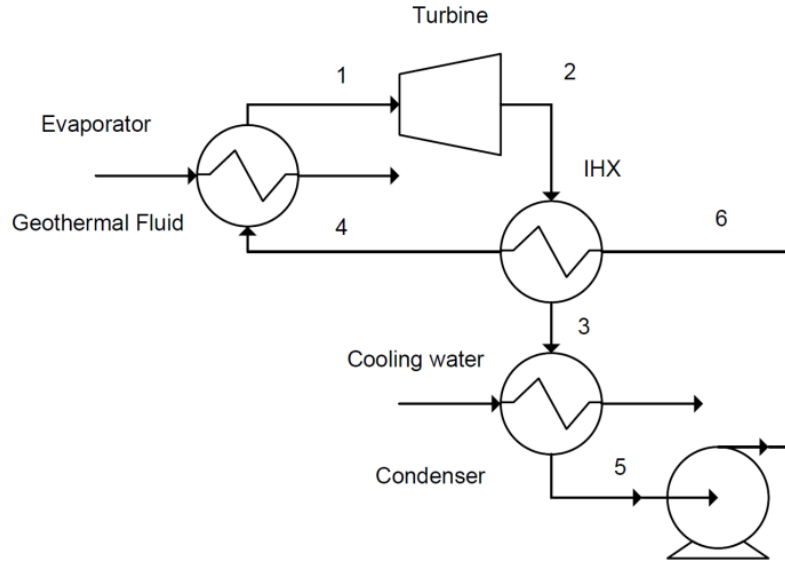


Figure 5: Rankine cycle with regenerator

Methodology

Thermodynamic analysis:

In modelling cycles, taking into account the following assumption, the laws of mass conservation and energy balance have been used (Li W., Feng X., Yu L. J., Xu J., 2011).

- The pressure drop in the heat exchanger, condenser and pipes is neglected.
- The isentropic efficiency of the turbine and pump is 85%.
- The geothermal fluid is saturated in its source.

Mass balance

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (2)$$

Energy balance:

$$\sum E_{in} = \sum E_{out} \quad (3)$$

Work of turbine:

$$\dot{W}_t = \dot{m}_{wf}(h_1 - h_2) \quad (4)$$

Work of pump:

$$\dot{W}_p = \dot{m}_{wf}(h_4 - h_3) \quad (5)$$

Heat output condenser:

$$\dot{Q}_{out} = \dot{m}_{wf}(h_2 - h_3) \quad (6)$$

Energy balance of condenser:

$$\dot{m}_{ct}(h_y - h_x) = \dot{m}_{wf}(h_2 - h_3) \quad (7)$$

Energy balance of preheater:

$$\dot{m}_b C_b (T_b - T_c) = \dot{m}_{wf}(h_b - h_4) \quad (8)$$

Heat of preheater:

$$\dot{Q}_p = \dot{m}_{wf}(h_5 - h_4) \quad (10)$$

Heat input by evaporator:

$$\dot{Q}_{in} = \dot{m}_{wf}(h_5 - h_1) \quad (11)$$

Cycle thermal efficiency:

$$\eta = \frac{\dot{W}_t - \dot{W}_p}{\dot{Q}_{in}} \quad (12)$$

Table 1:Nomenclature

$\dot{W}_t$ (kW)	power of turbine
$\dot{W}_p$ (kW)	power of pump
H_{cycle} (%)	cycle thermal efficiency
$\dot{m}_{wf}$ (kg/s)	mass flow rate of working fluid
$\dot{m}_b$ (kg/s)	mass flow rate of brine
$\dot{m}_b$ (kg/s)	mass flow rate of water
h_1 (kJ/kg)	enthalpy of turbine
h_2 (kJ/kg)	enthalpy of condenser
h_3 (kJ/kg)	enthalpy of pump
h_4 (kJ/kg)	enthalpy of preheater
h_5 (kJ/kg)	enthalpy of evaporator
h_b (kJ/kg)	enthalpy of brine

h_y (kJ/kg)	water enthalpy of condenser
h_x (kJ/kg)	water enthalpy of condenser
c_b (kJ/kg.K)	heat capacity of brine
T_b (C)	input temperature of brine
T_c (C)	output temperature of brine
Q_{in} (kW)	output temperature of brine
Q_{out} (kW)	heat of condenser
Q_p (kW)	heat of preheater

Stimulation:

There are various methods in thermodynamic design of an Organic Rankine Cycle. Flow rates, temperatures and cycle operating pressures are the most important parameters and determining these parameters for different operating points is not an easy task. Because the point-to-point study of the cycle, the heating and cooling source and the interaction of three of these three parts should not overlap with each other and the difference of pinch temperatures in them should be determined correctly according to the intended goals. Therefore, it is best to first simulate a cycle similar to the one which was previously examined, and simulate the Organic Rankine Cycle with the desired working fluid based on the data.

The Organic Rankine Cycle sample, normal pentane working fluid with heat source of 165 °C is simulated with the data in the table below (Otong Nurhilal, Cukup Mulyana, Nendi Suhendi, et al., 2016).

Table 2: Simulation data

Parameter	Value
Atmosphere pressure (P_0)	1 atm
Ambient temperature (T_x)	27 C
Brine input temperature (T_b)	165 C
Brine output temperature (T_c)	100 C
Brine pressure (P_A)	8 bar
Brine mass flowrate	15 kg/s
Generator Efficiency	80%
Net Power	1 MW

Pinch Point Evaporator-Preheater	5 C
Pinch Point condenser	5 C
working fluid flowrate	15.51 kg/s

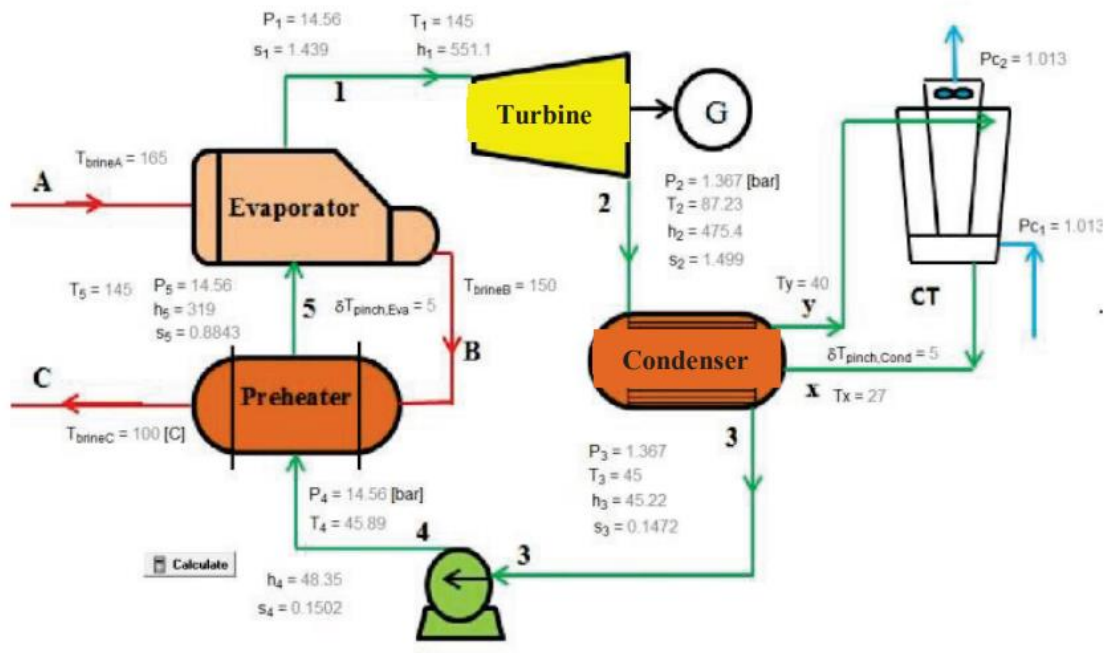


Figure 6: Windows diagram from the simulation

The following results were obtained according to the data in the table below.

Table 3: The result of simulation

Q_{in}	6672.1 kW
W_p	204.62 kW
Q_{out}	7796.1 kW
Cycle thermal efficiency	14.61%
Inlet temperature of turbine	145 C
Inlet pressure of turbine	14.56 bar
Power of turbine	1173 kW

It can be argued that the basis of numbers and simulation was correct based on simulating this example with the HYSYS program and comparing the results together which it was approximately same.

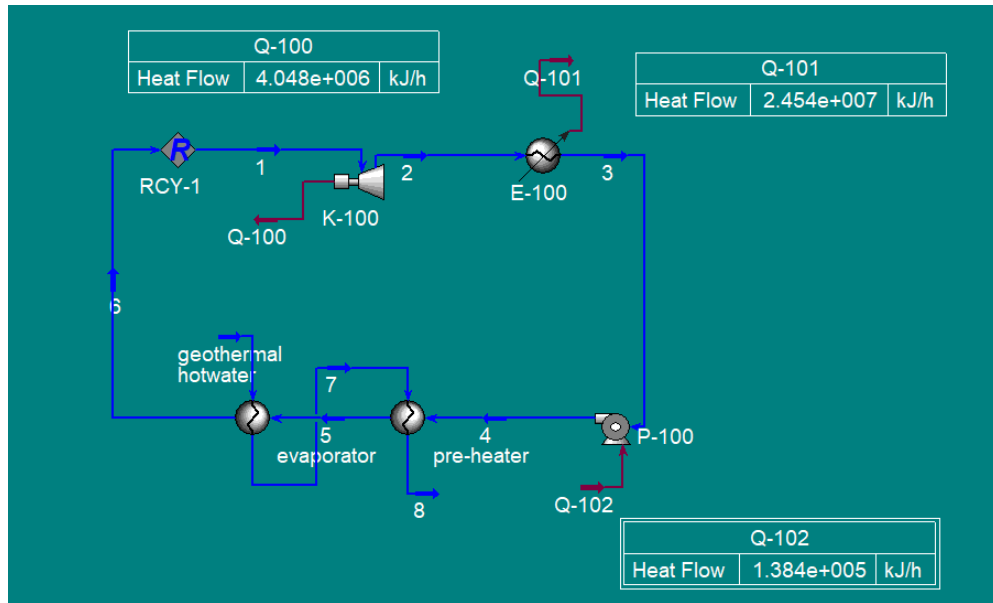


Figure 7: HYSYS simulation

Using the conditions of this example, the Rankine Cycle for Iso butane working fluid is simulated in the HYSYS program. The initial data of this cycle are given in the table below.

Using the conditions of this example, the Rankine Cycle for Iso butane working fluid is simulated in the HYSYS program. The initial data of this cycle are given in the table below.

Table 4: Assumption data

I-butane flow rate	20 kg/s
Geo hot water flowrate	54 kg/s
Geo hot water temperature	145 C
Geo hot water pressure	4 bar
Pump isentropic efficiency	85%
Turbine isentropic efficiency	85%
ΔP of pump	23.4 bar
ΔP of turbine	20.4 bar

And the results of this simulation are stated below.

Table 5: The result of simulation

Point	Temperature (C)	Pressure (bar)	Mass enthalpy (kJ/kg)	Mass entropy (kJ/kg-C)
1	144	4	13211	9.620
2	133.6	3	13291	9.554
3	120.2	2	13354	9.574
4	43.99	29	2613	1.587
5	118.6	28	2397	2.201
6	116.5	27	2226	2.645
7	58.51	6	2282	2.675
8	42	5	2618	1.586

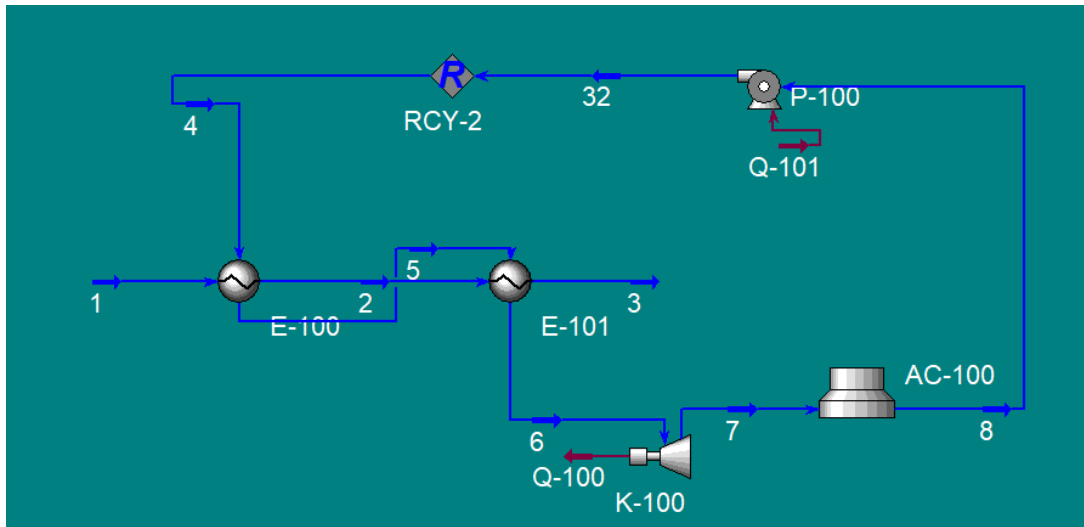


Figure 8: Simulation in HYSYS

This simulation is of the first model of the Rankine Cycle and the results of this first model simulation are written in the table below.

Table 6: Results

Q_{in}	7730.80 kW
Q_{out}	6712.15 kW
W_{pump}	104.2 kW
$W_{turbine}$	1218 kW
Cycle thermal efficiency	0.157

By obtaining these results, it can be concluded that the Iso butane working fluid had a more suitable efficiency for the Rankine Cycle. Now, by simulating the second model of the Rankine Cycle, the efficiency and energy consumption of these two models can be compared. Does the second model always increase the efficiency of the cycle or not?

In the first model, there are two heat exchangers in the heating part of the cycle, one of which is responsible for preheating the working fluid with the help of geo hot water and the other for evaporating the operating fluid.

In the simulation of the second model, like the first model, there are two heat exchangers, one of which is responsible for preheating the working fluid with the help of heat output from the turbine (regenerator) and the other is responsible for evaporating the working fluid. The simulation of the second model is as follows in the HYSYS program.

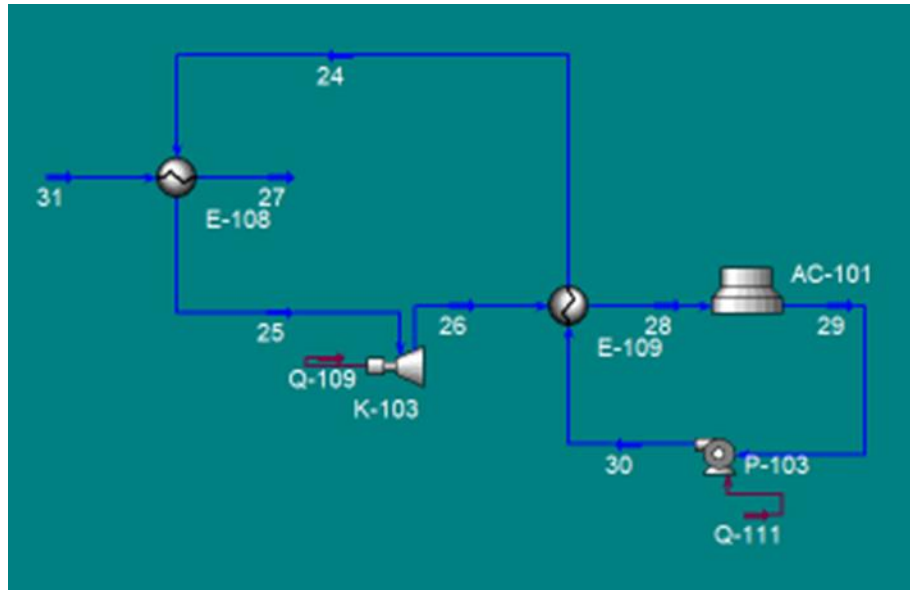


Figure 9: Stimulation in HYSYS

The results of this simulation are shown in the following tables.

Table 7: Results

point	Temperature (°C)	Pressure (bar)	Mass enthalpy (kJ/kg)	Mass entropy (kJ/kg-C)
24	49	28.5	2599	1.631
25	118.6	28	2224	2.641
26	57.23	5.8	2275	2.668
27	114.6	12	15494	4.129
28	49.6	5.6	2289	2.630
29	41.71	5.4	2618	1.586
30	43.69	29	2613	1.587
31	145	12	15356	4.474

Table 8: Results

Q_{in}	7495.06 kW
Q_{out}	6581.19 kW
W_{pump}	104.2 kW
W_{turbine}	1018 kW
Cycle thermal efficiency	0.145

According to the obtained data, these two models can be compared to each other. In the first model, the output power of the turbine is close to 1218 kW and also the efficiency of this cycle is approximately 15.7%, but in the second model cycle, its output power is close to 1018 kW and the efficiency of the cycle is approximately 14.5 %. By comparing these data, it can be concluded that with a slight difference, the first model of the Rankine Cycle is more economical.

Equipment sizing

Heat exchanger:

Shell and tube heat exchanger:

It is an equipment used to transfer heat from one fluid to another in the heating and cooling system. Takes one of the most common types of converters called Shell and Tube heat exchanger. It is a heat commonly used in oil refineries and large process factories. This type of converter consists of a pressurized tank (shell) and a set of closely spaced parallel tubes (bundles). Shell and tube heat exchangers work according to the principles of heat transfer by heat conduction method. As fluids flow through the tubes, heat is transferred from hot fluid to cold fluid, and vice versa. Therefore, the fluid inside the system reaches the desired temperature and exits the converter for reuse. Shell and tube heat exchangers are used in cooling, preheating, steam generation, steam recovery and similar operations. There are many types of shell and tube heat exchangers available in the market. The capabilities, benefits, and limitations of each of these converters are different. Of course, high flexibility in the design of this type of heat exchanger allows it to be used in different industries and different operating conditions. In a shell-and-tube heat exchanger, the amount of heat transfer between two fluids depends on the amount of fluid in the shell that contacts the surface around the tubes. This parameter is a function of the number of tubes in the converter (Subramanian, n.d.).

Heat transfer in a heat exchanger is such that the amount of heat lost in the hot fluid is equal to the amount of heat gained in the cold fluid.

$$Q = m_{hot} C_{P,hot} (T_{hot,in} - T_{hot,out}) = m_{cold} C_{P,cold} (T_{cold,out} - T_{cold,in}) \quad (13)$$

$$Q = UAF\Delta T_{lm} \quad (14)$$

$$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left[\frac{(T_1 - t_2)}{(T_2 - t_1)}\right]} \quad (15)$$

Table 9: Nomenclature

T₁	Hot flow in
T₂	Hot flow out
t₁	Cold flow in
t₂	Cold flow out
F	Correction factor
U(W/m-C)	Overall heat transfer coefficient

To obtain the overall heat transfer coefficient, the following formula is used:

$$\frac{1}{UA_s} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = R = \frac{1}{h_i A_i} + R_{wall} + \frac{1}{h_o A_o} \quad (16)$$

But by simplifying the equation, the heat transfer coefficient can be calculated using the following formula (Yunus A. Cengel, n.d.).

$$\frac{1}{U} \approx \frac{1}{h_i} + \frac{1}{h_o} \quad (17)$$

To get Convection coefficient of tubes, the tubes use dimensionless numbers such as Reynolds, Prandtl, and Nusselt as follows.

$$Re = \frac{VD}{\nu} \quad (18)$$

$$Pr = \frac{c_p \mu}{k} \quad (19)$$

$$Nu = \frac{h_i D}{k} \quad (20)$$

To reduce the error percentage in the equations, the Nusselt number is used with the help of the equations Gnielinski (Abraham, J. P., Sparrow, E. M. & Tong, J. C. K., 2009) and Petukhov (Petukhov, 1970).

$$f = (0.790 \times \ln(Re) - 1.64)^{-2} \quad 3000 < Re < 5 * 10^6, \quad (21)$$

$$Nu = \frac{\left(\frac{f}{8}\right)(Re-1000)Pr}{1+12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{2/3}-1\right)} \quad 3000 < Re < 5 * 10^6, 0.5 \leq Pr \leq 2000 \quad (22)$$

The calculation of the convection coefficient of shell cannot be obtained by this method due to the presence of baffles inside the shell. To increase the accuracy of the numbers, according to research, we can use the equations of Donohue (Donohue, 1949).

$$G_b = \frac{\dot{m}_s}{\frac{\pi}{4}(f_B D_s^2 - N_{bt} D_i^2)} \quad (23)$$

$$G_c = \frac{\dot{m}_s}{P_B D_s \left(1 - \frac{D_i}{P_T}\right)} \quad (24)$$

$$Nu_o = \frac{h_o D_s}{k} = 0.2 \left(\frac{D_i \sqrt{G_b G_c}}{\mu} \right)^{0.6} Pr^{1/3} \quad (25)$$

Table 10: Nomenclature

G_b	Mass velocity of shell side moving parallel to tube
G_c	Mass velocity of shell side moving across the tubes
f_B	Baffle fraction
D_s	Shell diameter
d_o	Tube diameter
N_{bt}	Number of tubes in the baffle cut
P_B	Baffle spacing
P_t	Length of the tube pitch

Hypotheses must be considered to obtain the total surface area of the pipes. These hypotheses have been removed from the HYSYS program.

Table 11: Assumption

f_B	0.2
D_s	1.6 m
d_o	0.02 m
P_B	0.8 m

P_t	0.05 m
d_i	0.016 m
Tube length E-100	6 m
Tube length E-101	6 m

According to the assumptions of this table, the total heat transfer coefficient can be calculated and through the table you can also obtain the total surface of the pipes and its number.

Table 12:Results

U_{E-100} (w/m-C)	859.63
A_{E-100} (m²)	105.74
Number of tubes in E-100	246
U_{E-101} (w/m-C)	1284.92
A_{E-101} (m²)	376.51
Number of tubes in E-101	753

According to research done in different conditions for heat exchangers, a certain range of overall heat transfer coefficient has been considered. For example, it is between 300-1200 when it acts as a preheater in a shell-and-tube heat exchanger, and between 900-1300 when it acts as an evaporator (Yunus A. Cengel, n.d.).

In this cycle, one of the most important equipment is the condenser section, because due to the fact that this section is located in the southern part of Iran, the ambient air is very effective in performing operations.

Air cooler:

In this cycle, the heat exchanger located in the condenser section is considered as an air conditioner model. The air cooler is such that with the help of fans, it uses the ambient air and the air passes through the pipes with a certain speed and a certain volume flow. The fluid inside the tube exchanges heat with the air. In this project, its average annual temperature is 35 degrees Celsius since the system is located in the south of Iran. To obtain the required number of pipes in the air cooler, the same method of heat exchanger shell and tube is done. The heat transfer coefficient range in air cooler is between 350-500. Due to the fact that the heat transfer interval is low and LMTD is relatively low, the amount of heat transfer level increases and the same occurs with the number of pipes. To prevent an increase in the number of pipes, a fin can be used to increase the heat transfer level of each pipe (Ulrich, 1984).

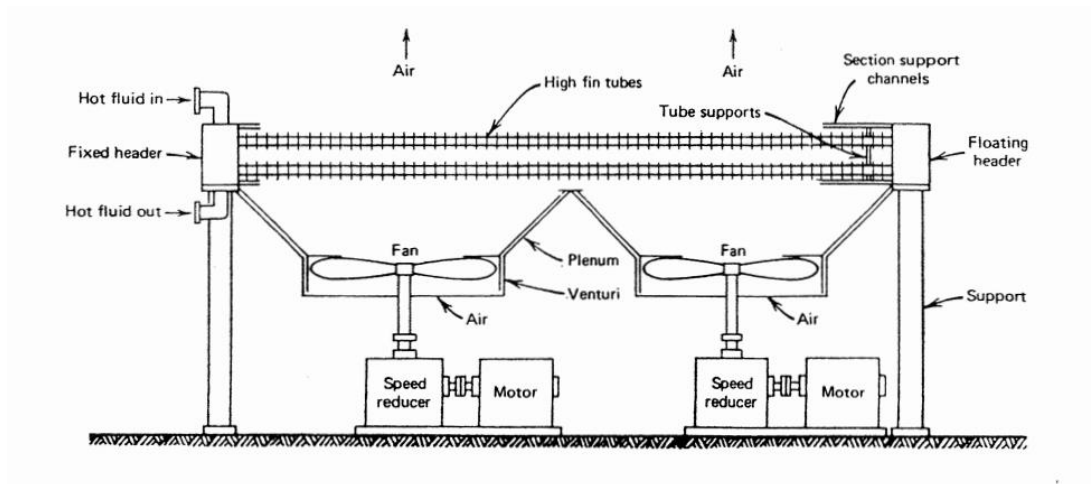


Figure 10: Air cooler

Fins, depending on their type, also affect important factors such as increased heat transfer as well as cost. In this air conditioner, G type is used, the specifications of which are given in the table below (661, 2002).

Table 13: Assumption about fins

type	G-finned
Fin diameter (mm)	57.15
Tube diameter (mm)	25.4
Fin thickness (mm)	0.28
Fin frequency (#/m)	433
material	Aluminum 1060

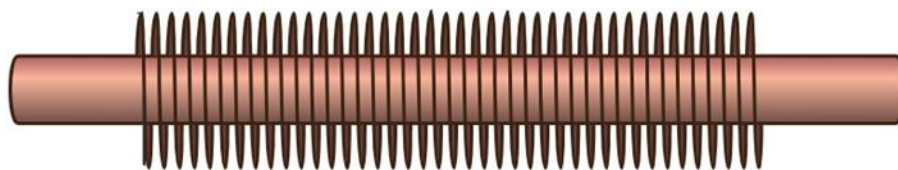


Figure 11: a sample of tubes with fins

By obtaining the amount of heat transfer coefficient and the surface of each pipe along with the fin, the number of pipes in the air conditioner can be obtained. In this system, the length of air conditioner pipes is considered as meters and the total heat transfer surface (including fan) is approximately 3791 m^2 . Through calculations, it can be seen that the number of pipes required in the air conditioner is 369.

Pump:

The pump is a very practical device in the field of engineering, without which many projects will be disrupted. The main function of the pump is to increase the pressure of transferring various fluids, which have been used by people in various ways since ancient times. Of course, the only important task of the pump is not to transfer fluid, and this device is also used to compress various liquids. In general, pumps are divided into two main categories, dynamic pumps and positive displacement pumps. In this system, the type of pump according to its needs is dynamic and the centrifuge model is used. The centrifugal pump is one of the most widely used pumps in the world because of its simple operation and production and the construction costs are very low. They are usually long-lived. The operation of these pumps is that increasing the pressure from the inlet to the outlet of the pump causes the movement of fluid. This pressure-generating force is supplied by an electric motor that forces the impeller to move. The fluid enters the center of the impeller and exits from its edges. The centrifugal force increases the speed and kinetic energy of the fluid.

To calculate the power of a water pump, it should be noted that the pump is a basic and important mechanical device that provides the force of fluid displacement with the desired flow, like any other equipment that does the work (to transfer energy conversion objects), its output is measured in units of power. There are two methods to calculate the pump power: 1- Using the enthalpy difference between the input and output pump 2- Obtaining the head loss of the pump

There are two pumps in this designed system. Its first function is to transfer water from the ground into the well. The pump must pump water at a flow rate of 54 kg/s into a 6-inch pipe and then pump it with 3 bar pressure into the Rankine cycle.

According to that, the depth of the well is 4000 meters and in fact the water has to travel a distance of approximately 8000 meters to be able to enter the heat exchanger. At this distance, a large part

of the energy is spent on the friction between the fluid and the pipe. The overall head loss is obtained based on the following formula (Pritchard, 2011).

$$h_{lT} = h_l + h_{lm} \quad (26)$$

The total head loss is the sum of the major losses (friction between the pipe and the fluid) and the minor loss (change of the pipe cross section, inlets and outlets, elbows, valves and fittings). Due to the condition of the pipe, the sub-loss is ignored. The following formula is used to obtain the original dissipation.

$$h_l = f \frac{L}{D} \frac{V^2}{2} \quad (27)$$

Speed can be obtained by having data on volumetric flow rate, cross section and fluid density. f is the coefficient of friction between the fluid and the pipe, which is a function of the Reynolds number, the diameter of the pipe and the roughness of the pipe. The material of the carbon steel pipe and its diameter is 6 inches.

Roughness of carbon steel (mm)	0.035
Pipe diameter (mm)	168
e/D	0.000208
Re	1.97E+06
f	0.013
H_l (m)	188.37798
	5

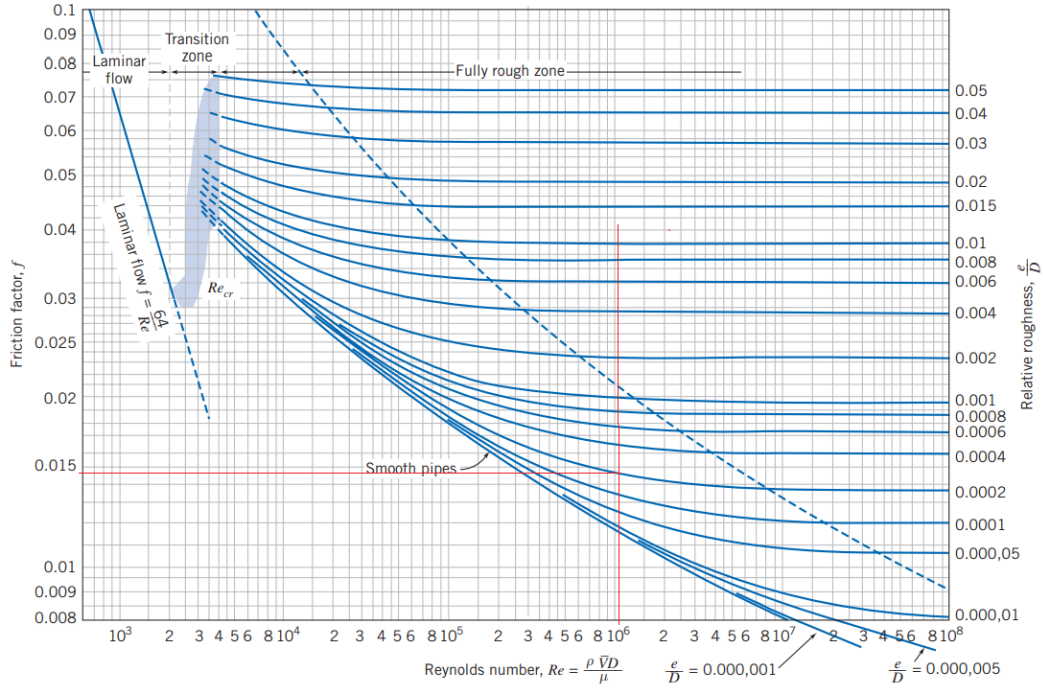


Figure 12: Friction factor for fully developed flow in circular pipes

In addition to the head loss that occurs inside the well pipe, a pressure difference for the well inlet and outlet must be considered. Water enters the well with a pressure of 1 bar and exits the well with a pressure of 12 bar and enters the heat exchanger.

Using the pump pressure difference, the required pump power can be obtained from the following equation.

$$\dot{W}_{pump} (kW) = Q \left(\frac{m^3}{s} \right) * \Delta P (kPa) \quad (28)$$

The power required for the water pump is 117 kW.

For the pump inside the Rankine cycle, information about the enthalpy of input and output can be obtained with the help of HYSYS, and with the help of equation 5 it can be found that the power consumption of the pump is 89 kW.

Steam turbine:

The turbine, as the most important part of a thermal power plant, is a machine that produces work that converts it into mechanical energy by taking heat energy and steam pressure. This mechanical power is then converted into electrical energy in a generator. The set of turbines and cycle

equipment, including feed water heaters, condensers, etc., are closely related and their performance is completely interdependent.

Each stage of the steam turbine consists of a series of nozzles or fixed blades that are installed on the turbine body and in multi-stage turbines are called guide blades, or stationary blades and a series of working blades that are located on the axis and blades which are called the working blade.

When the steam flow passes through the moving blades at high speed and pressure, the steam and energy flow hidden in the steam hits the turbine blades and is converted into rotational mechanical energy, causing the blades to move and as a result the turbine shaft moves to the turbine shaft. It becomes mechanical work and rotation of the turbine rotor. However, the expansion of steam in the nozzles and the passage of steam flow through the moving vanes cause a decrease in compressive, thermal and kinetic energy, which decreases the efficiency of each stage.

Since high pressure steam enters the turbine and low-pressure escapes from it, there is always a pressure difference inside the turbine, which creates an axial force from the high pressure to the low pressure on the turbine rotator shaft. To neutralize it, the turbine must be designed in such a way that the least axial force is applied to the rotors while the turbine is in operation.

Turbine efficiency, like any other system or equipment, is the work produced to the maximum power that can be produced (ideally). To calculate the efficiency of each turbine section, which is an independent section consisting of a number of floors with separate inlet and outlet and shell, We can use the following equations by determining the steam enthalpy (by measuring temperature and pressure) at the inlet and outlet of that part of the turbine.

The specific energy change of the fluid passing through the turbine is equal to the enthalpy difference of its inlet and outlet, which is equivalent to the actual work produced per unit mass of fluid passing through the turbine:

$$w_{actual} = h_{in} - h_{out} \quad (29)$$

Most of the work of an adiabatic turbine (insulation) is produced in a reversible state (constant entropy), which is a model of an ideal state without losses. Due to friction, steam leakage and other wastes inside the turbine, the actual work produced is always less than the ideal work. The ideal (isentropic) operating value of the turbine can be calculated by calculating the enthalpy of the output fluid if its entropy is equal to the initial entropy. In this project, the efficiency of the turbine is 80% and its output power is 1200 kW (Shahmansouri, 2009).

$$w_{ideal} = h_{in} - h'_{out} \quad (30)$$

$$\eta_{turbine} = \frac{w_{actual}}{w_{ideal}} \quad (31)$$

Economic Analysis:

The estimation and determination of the approximate true price for the devices and the equipment is very important for all engineers because to complete a project, it needs to be price efficient. The investor's assurance of the estimate industrial unit price can play a huge role in business/trade and any possibility of error, slip, and the worry of those might result in the transfer of investment. The investors should be sure of the return of their investment. The economic analysis is composed of the capital cost, the annual expenses, and the annual income. By having these numbers, the time of estimation for the return of investment and the profitability of the plan, will be lessened.

To calculate the capital cost, after finding the dimensions and specifications of the equipment, with the help of valid sources like Gael D. Ulrich book (Ulrich, 1984), the price of the equipment can be estimated. With the help of this source, the base price of an equipment with its special condition can be estimated and moreover the approximate price for the equipment can be found, using the correction factor coefficients. In this context, factors such as the year, material of equipment, the pressure the equipment must tolerate, etc. is effective to determine the price. The next crucial factor is the cost of installation of the equipment and that can be estimated by using the bare module (FBM) factor.

Table 14: Cost estimation of equipment

		Capacity of size specification	Purchase Equipment in 1982 (CEPI=315)	Purchase Equipment in 2022 (CEPI=776)	Real purchase cost in 2022	Installed cost in 2022
Heat Exchanger	AC-100	A=3790 m ²	100,000	246,349.20	246,349.20	739,047.619
	E-100	A=106 m ²	10,000	24,634.92	27,098.41	94,844.44
	E-101	A=376 m ²	30,000	73,904.76	81,295.23	284,533.33
Pump	P-100	W _s =101.88	18,500	45,574.60	68,361	341,809.69
	P-101	W _s = 133.45	25,000	61,587.30	123,174.6	404,012.69
Turbine	K-100	W _s =1360	100,000	246,349.20	246,349.20	862,222.22
Total				698,399.68	767993.6508	2,726,469.841

After finding the capital cost, the annual income must be calculated. The goal of this project is to generate and distribute power for household use but meanwhile there is equipment like pumps that use up a lot of power. In this project, the amount of usable power is approximately 1012 kilowatt which is equal to 8743 megawatts hour for an electric consumption in a year. If the average consumption for a 3–4-person household in south of Iran is estimated to be 1000 kilowatts (with

the consideration that air conditioning systems are mostly gas coolers in the South) it can be assumed that the power generated from the Rankin cycle can generate the household power needed for 1000 families in the south of Iran. The cost for 1 kilowatt hour in the tropical regions according to the declaration of the Electricity Organization of Iran, is considered 5000 Rials. With the specified number, the price of usable electricity is around 47 milliards annually which is equivalent to 189741 USD.

The third step in economic analysis is the estimation of annual expenses. As a whole, the yearly expenses are divided into 3 parts: direct, indirect, and general. In the direct expenses section, there is costs such as buying the raw material, workers wage/salary, cost of maintenance and repair. The indirect expenses include insurance and taxes, and the annual general expenses include research, the cost of distribution, sale and managing. Given that this system is a simple package, most mentioned variables can be excluded. In this system, the main material is isobutane and the cost for each 124 cubic meters of it is equal to \$7000, but due to the fact that this isobutane goes in a cycle, the cost of it can be considered as the initial investment and the used-up water can be taken from the sea as well. This cycle needs an operator to check the necessary data daily. The annual operator's salary can be estimated for about \$2600. Considering that the equipment of the Rankin cycle are very sensitive such as the heat exchangers that over time may settle into water sediments, and/or the pumps and turbines might break down, therefore, in this system, the annual expense for maintenance and repair should be around \$30000. Moreover, a cost of \$4800 should be considered for managing the package. All in all, this system's expenses are in total \$37000.

With deducting the annual expenses from the calculated cost for generating electricity, it can get the annual income. Part of this income goes to taxes. According to the government statement, public institutions must pay 10% of their total income, therefore, the annual net income of this system can be found using this formula:

$$A_{NCI} = A_{CI} - A_{IT} \quad (32)$$

This graph has been illustrated by data and with the use of this graph, the efficiency or nonefficiency of this project can be figured.

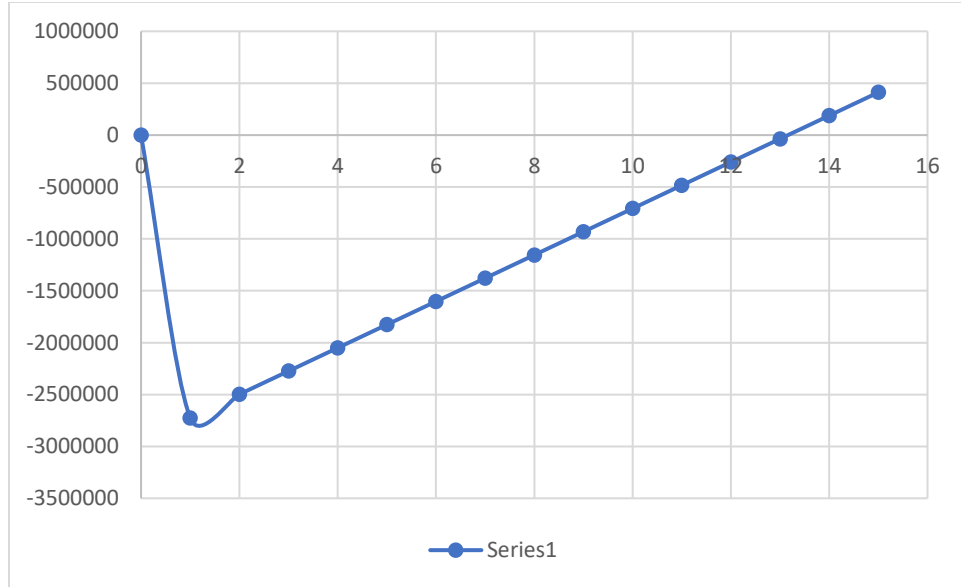


Figure 13: Cumulative cash flow

As it is shown, the life of this system is 15 years. Approximately after 13 years, the initial investment will be returned which is not logical for the investors. Due to the low cost of electricity in Iran, with this amount of electricity generation it is not worth it.

Results and conclusions

In the science of thermodynamics, 3 factors can increase the efficiency of the Rankine cycle which include increasing the inlet temperature of the turbine, increasing the evaporator pressure, and decreasing the condenser pressure. In the Rankine cycle, the operating fluid in the condenser is present as a saturated vapor at a saturation temperature. The amount of this saturation is determined according to the operating pressure so that by reducing the pressure in the condenser, the temperature of the working fluid decreases and increases the Rankine efficiency. An important point to note is that in this case, the quality of the working fluid at the turbine output has decreased and its moisture content has increased. Excessively reducing the quality of the working fluid and thus increasing its humidity at the turbine outlet, reduces the performance of the turbine and affects the overall efficiency of the Rankine cycle. Therefore, to increase the efficiency using the condenser pressure reduction method, there is a limit, and the condenser operating pressure can not be less than a certain value. In addition, since the cycle is launched in the south of Iran, the condenser of this cycle condenses the working fluid through an air conditioner with ambient air. Moreover, the inlet fluid temperature should not be lower than the ambient temperature, so the condenser inlet pressure cannot be greatly reduced.

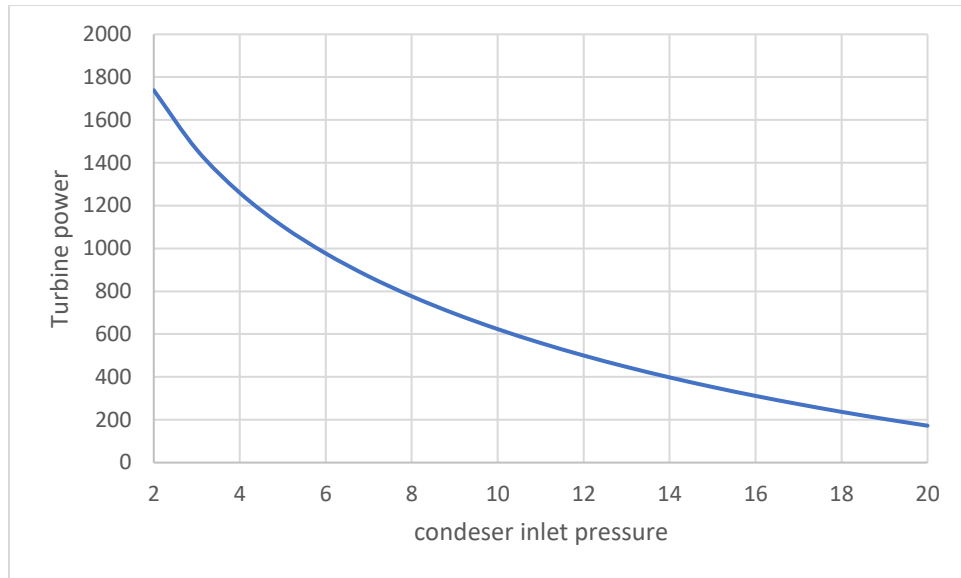


Figure 14: Relation between pressure of condenser and turbine power

Another way to increase the efficiency of the Rankine cycle is to increase the average temperature at which the working fluid is heated. This can be done by overheating the working fluid before entering the turbine. Thus, by overheating the working fluid at the turbine inlet, the required inlet heat and net operation are increased. The final effect of these two parameters increases the efficiency of the Rankine cycle. It is important to mention two points in this method. The first point is that overheating the working fluid reduces the moisture content of the turbine output saturation composition (of course the problem can be solved with the help of a regenerator). The second point is that the inlet temperature of the turbine cannot be increased by a large amount and the rate of temperature increase is determined according to the material and structure of the turbine. Also, because the earth temperature is known, this factor cannot be considered as an auxiliary variable.

Increasing the evaporator pressure, the temperature at which boiling occurs and thus increases the average temperature of the working fluid while receiving heat, improves the efficiency of the Rankine cycle. The isobutane critical pressure is 37 bar, but it is important to note that if the operating fluid pressure in the evaporator increases, it will also increase the fluid temperature. Because the task of evaporating the operating fluid is the responsibility of the shell and tube heat exchangers, the initial temperature of the fluid should not exceed the heated water temperature of the well. Another point is that excessive increase of evaporator pressure also reduces the performance of the turbine. According to the following diagram, it can also be concluded that in isobutane, when the pressure exceeds 35 bars, the turbine performance and efficiency decreases.

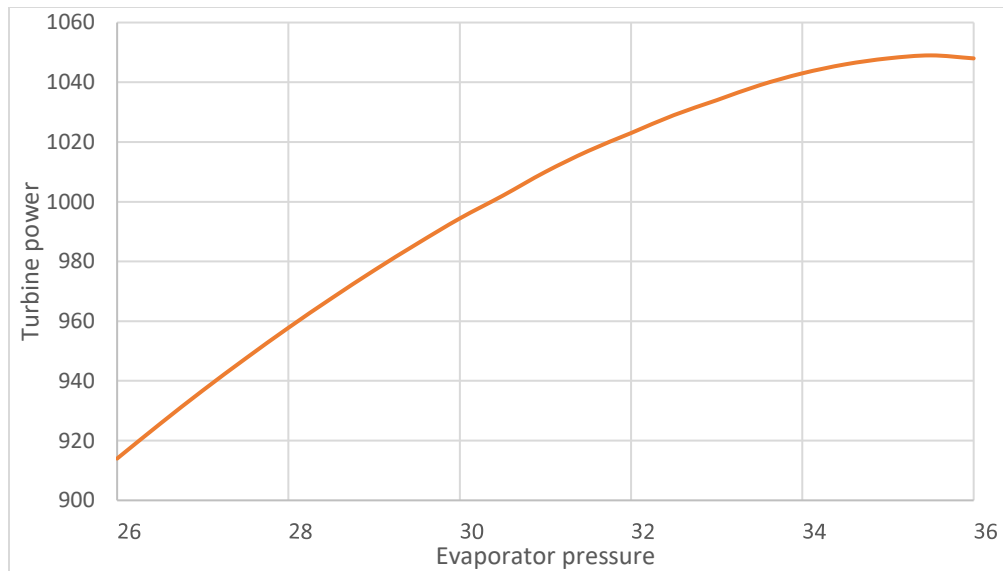


Figure 15: Relation between evaporator pressure and turbine power

In addition to the factors above, environmental conditions such as ambient temperature affects the performance of the Rankine cycle and its efficiency. Rising ambient temperature has a negative effect on the performance of the air cooler condenser because it increases the power consumption of the fans. But this effect occurs considerably at high ambient temperatures. At high ambient temperatures, the net output power of the Rankine organic cycle is limited by the capacity of the air conditioner. This means that whenever the temperature of the air entering the condenser changes, if the cooling takes places with the required amount, the mass flow rate of the air entering should increase and it is necessary to increase the fan speed. Therefore, the power consumption and consequently the power of the capacitors increases. But it is noteworthy that to neutralize the negative effect of increasing temperature, increasing the mass flow rate of the working fluid can be used. Changes in working fluid rate are directly related to Rankine organic cycle efficiency. Therefore, in the hot season in southern Iran, where the average temperature is between 30 to 45 degrees Celsius, the isobutane discharge should be more than 20 kg/s.

The inlet pressure of heated water to the heat exchanger is a variable that is not very limited, but, according to comparisons, pressure with changes between 1 to 10 bar has no effect on turbine performance. Therefore, to reduce the cost of the pump's well, it is better to consider the lowest possible pressure. Due to the fact that each heat exchanger has a pressure drop equal to 1 bar, the heated water pressure is considered 4 bars to avoid negative pressure.

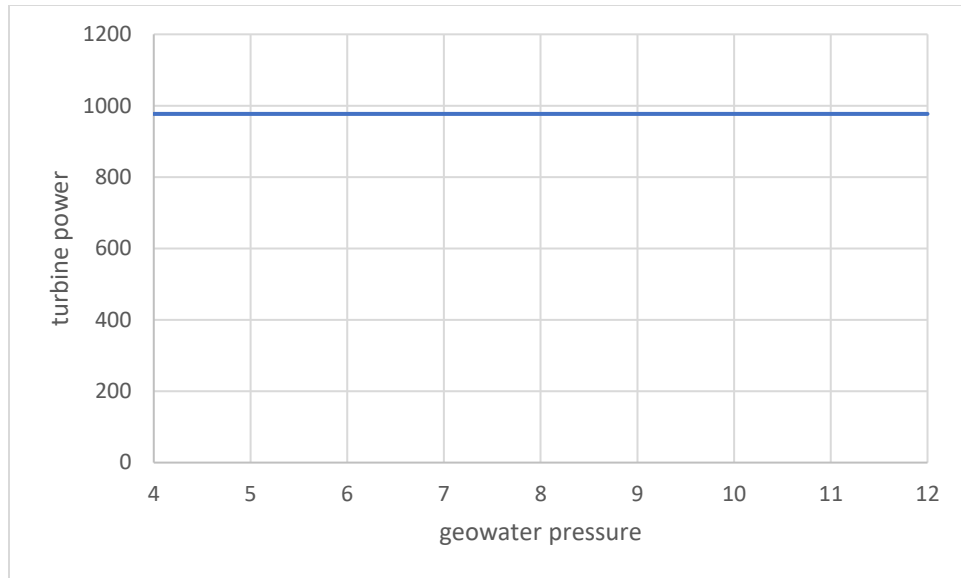


Figure 16: Relation between hot geowater pressure and turbine power

In general, to design this system, it is better to determine the amount of its budget beforehand and according to that identify the average volume of equipment and raw materials. In addition, climatic conditions and the pits characteristics are very important. It is better for the well to be deep enough that its maximum temperature is 160 degrees Celsius and because the cycle takes heats from the water, it is better for the well to be close to the sea. But the most important point is that climatic conditions of the plant must be suitable because the important and basic part of this system is the presence of condensers. For better performance of condensers, it is better to have suitable ambient air. In hot seasons, the mass flow rate should be higher, so equipment should be designed to be usable for all seasons. Moreover, to make more use of the Rankine cycle, the heat of several adjacent wells can be used, but this issue must be considered from an economic point of view and the choosing of the size of equipment should be done more carefully.

All in all, given that the economic situation in Iran is different from other countries and due to the low cost of electricity, economic analysis may not be citationable.

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