Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Suitable Power Plant Selection for High Enthalpy Geothermal Fields of Turkey

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Keywords: Double flash system, bottoming binary cycle, combine cycle, optimization.

ABSTRACT

There are various geothermal resources with different temperatures in Turkey. Some of them are resources with middle enthalpies, and therefore, binary type power plants are suitable solution for them. Single and double flash processes have already been installed for higher enthalpy resources in our country. In recent years, in order to increase the efficiencies of flash geothermal processes, bottoming binary and combined geothermal power plants have been introduced in the industry for higher enthalpy geothermal fields.

In this study, old flash processes are compared with new combined systems; advantages and disadvantages are reported, and suitability of them for Turkish geothermal resources has been discussed and results are presented. Several solutions are considered for higher enthalpy resources. The first model is double flash process with efficiency of 10% compared with the second solution of single flash with bottoming binary model with efficiency of 12%. And the last model is combined cycle solution and its efficiency is calculated as 13%. In selection of suitable plants together with efficiencies silica scaling and high CO_2 content issues are also taken into account.

1. INTRODUCTION

First geothermal power plant installed in 1904 was a process composed of piston engine, which was fed by a vapor dominated geothermal system. Later on in 1930s and 1940s, similar processes enhanced by condensers have been installed in Larderello area. First geothermal power plant based on flash process fed by water dominated systems was installed in 1958 at Wairakei, New Zealand. Afterwards, in 1960s and 1970s, beside single-flash processes, double-flash processes for higher enthalpy geothermal fields have been installed and operated. In 1980s first prototype binary geothermal power plants were introduced and they were started to be widely used in 2000s. As seen from aforementioned, geothermal power plant technology has greatly improved in the last 50 years.

Geothermal power plants, which are essentially thermal plants, and are operated as base-load power plants like them. They also differ from thermal plants for having lower efficiencies due to low resource temperatures. As they depend upon underground resource, they are dependent upon not only resource temperatures, but also physico-chemical properties of those resources. In this context, scaling is also a major issue to be taken into account in designing geothermal power plants. High carbon dioxide content of Turkish geothermal resources is also a major concern in power plant design. Therefore, power plant type selection is a very critical and important issue.

The highest power generation from geothermal resources which is used from all over the world of countries is the Philippines, Indonesia, Italy and Mexico. According to the 2013 data, the total of generating capacity by geothermal sources was 11772 MWe (IGA, Installed Generating Capacity List). The developing power plant technologies for the middle or low temperature and water-dominated geothermal resources are produced electricity (DiPippo 2005). Especially, binary and combined systems are the most important cycles of power plant technologies.

In this study, different models of processes are compared each other for a geothermal source of Turkey. These models are Double Flash, Bottoming Binary and Combined cycle systems. The models of these types of cycles, all parts of power plant units are optimized and the optimal operational conditions are identified. As a result of calculations, the net electrical power of all models is compared, and the most efficient model and optimal operational conditions are determined.

2. GEOTHERMAL POWER GENERATING SYSTEMS

Previously, geothermal fluid was used for only cooking or heating, than the first field studies began for the production of boron in Italy in 1833. First geothermal power plant of Larderello field that was used to vapor dominated geothermal system, installed in 1904 in Italy. The following years, many countries continued to field study. The first geothermal drilling in Turkey was carried out in 1963. Then, the Kızıldere field was discovered in 1968.

According to the EMRA (Energy Market Regulatory Authority) 2012 data, geothermal based projects have reached a 160.7 MW_e installed capacity and total licensed projects have a capacity of 700 MW. Total installed power generation capacity of Turkey is about 53,235 MW_e (Aksoy 2013).

Most of the geothermal energy sources in the world is two-phase liquid-dominated and contain high percent of dissolved CO_2 that cause the scaling problem.

For the power generation from moderate enthalpy geothermal sources, binary systems are developed. The principle of producing electricity of Binary system is using a working fluid to transfer heat from geothermal fluid. Also, the bottoming binary system and the combined system are developed of middle or low enthalpy geothermal systems.

2.1 The Power Generating Systems of Two- Phases Water Dominated Geothermal Sources

If the geothermal resource is two-phase water dominated system, the steam phase flashed within the wellbore must be separated from liquid phase before the steam came into turbine. For this reason, when the power generation done using two phase-flow from geothermal sources, the separator is used. One or two separator is used for power generating systems. If one separator is used, the system will be called the single flash power generating system. The single flash system has to be one separator and one turbine-cooling systems. After the geothermal fluid comes into the separator, steam goes to turbine directly and brine will be injected to formation.

In order to obtain more energy from flash system, two separators are used. The system is called double flash that includes two separators with a two- stage turbine. After the first stage separation, steam goes to the first stage of turbine with high pressure. And then, brine will be transferred to the second separator. After the second flash processes, steam will be getting into the low pressure parts of the same turbine or other low pressure turbine directly to get more energy. The exhaust pressure of turbine is to be under the atmospheric pressure. These non-condensable gases must be extracted from the condenser by a pump or ejector (Serpen 2010). Figure 1 shows that the schematic flow of double flash power generating system.

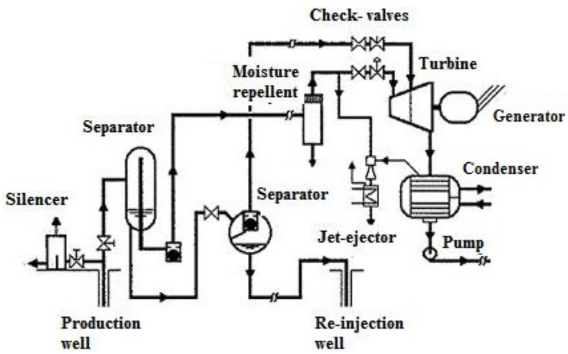

Figure 1: Simplified schematic of double flash geothermal power plant (DiPippo 2005).

2.2 Binary System Power Plants

For electricity generation from low- temperature (<180 °C) and water- dominated geothermal sources, heat energy from geofluid is transferred to a working fluid. The binary system is essentially a Rankin cycle. The working fluid receives heat from geothermal fluid, evaporates and expands through the turbine or expander. It condenses and is returned to the evaporator through a preheater.

The working fluids are generally hydrocarbons such as n-pentane, iso-pentane, butane, and iso-butane or refrigerants such as R134a. The working fluids are used rather than water because they have low boiling temperatures. So power generation from low reservoir temperature geothermal sources, becomes advantageous. Figure 2 shows that the schematic of basic binary power plant.

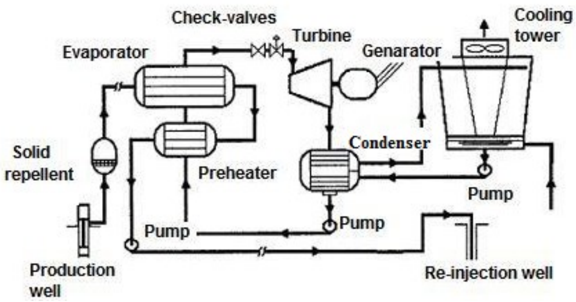

Figure 2: Simplified schematic of binary geothermal power plant (DiPippo 2005).

2.3 Combined System Geothermal Power Plants

The combined system geothermal power plants are developed to obtain more energy than other processes from geothermal sources. In general, these systems include different types of cycles. The most commonly used is bottoming binary type geothermal power plant. The bottoming binary cycle has a single flash system and binary cycle together. Figure 3 shows that the schematic of flow of bottoming binary power plant.

According to Figure 3, numbers refer to path of geothermal fluid moving in the plant. Between 1 and 7, geothermal fluid is used to produce electricity in single flash system. Also, between a-f is working fluid path in binary cycle. After the separation of geothermal fluid, brine goes to binary cycle directly, (point 3). After the heating transfer between geothermal fluid and working fluid of binary cycle, the geothermal fluid is re-injected into the formation.

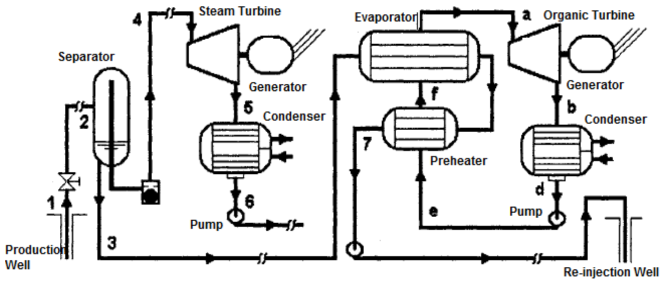

Figure 3: Simplified schematic of bottoming binary geothermal power plant (DiPippo 2005).

3. POWER PLANT DESIGN FOR A GEOTHERMAL SOURCE IN TURKEY, SYSTEMS ANALYSIS

This study investigates that three different power plant model design for a typical high enthalpy geothermal source in Turkey. In calculating of different power plant processes, we use the same parameters, such as; reservoir condition of geothermal source, wellhead pressure, wellhead temperature, weather conditions, non-condensable gases in steam, and the efficiencies of turbine, generator, pump, and cooling tower fan. Constants that are used for each model are shown in Table-1.

Table 1: Model Parameters

	Unit	Value
Reservoir temperature	°C	240
Wellhead pressure	Bar	19
Wellhead two-phase fluid enthalpy	kJ/kg	943
Total flow rate	Ton/h	1155
Non-condensable gases in steam (% weight)	%	15
Non-condensable gases		CO_2
Steam turbine efficiency	%	80
Organic turbine efficiency	%	85
Generator efficiency	%	95
Pump efficiency	%	80
Pump motor efficiency	%	90
Cooling tower fan efficiency	%	50
Atmospheric pressure	Bar	0.959
Average monthly air temperature	°C	16
Average monthly relative humidity	%	61
Relative humidity to the air from the cooling tower	%	90

Geothermal fluid contains a high enthalpy, two-phase and non-condensable gas mixture. So, the separator must be used for power plant design. For all designed power plant models, webre type cyclone separator is used. The most important parameter of separator analysis is flash pressure. The amount of steam extracted after separation processes depends on this pressure. Separator analysis based on first rule of thermodynamics that is the mass and energy conservation.

Another important analysis of power plant design is turbine- generator analysis. Expansion process of turbine is assumed a continuous- adiabatic thermodynamic system, and kinetic and potential energy loses will be zero. Maximum turbine work is obtained during the isentropic and adiabatic expansion process.

The analysis of condenser is another effective process for generating energy in a geothermal power plant. The general criteria of condenser analysis are dropping temperature of turbine exhaust and condense of all fluid where turbine exhausts (Gökçen and Özcan 2008, Holman 1988). Using first rule thermodynamics, the analysis of condenser is basically done.

For this study, we assume that all of the non-condensable gases are CO_2 and the jet- ejector pump unite can be used for separation of NCG. Figure 4 shows that the jet-ejector pump for using all models of this study.

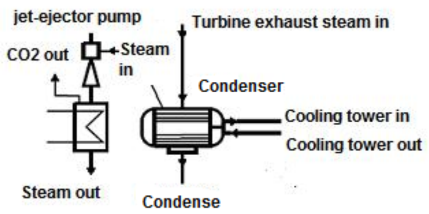

Figure 4: Simplified jet-ejector pump system schematic (DiPippo 2005).

Moreover, this study also includes pump, cooling- tower, evaporator and preheater analysis for all models.

Cooling tower is used to reduce the temperature of the condensing fluid. Air and water cooled types are available. In this study, the air cooled type cooling tower is selected for binary systems. The cooling tower analysis depends on the mass and energy conservation rule of thermodynamics. As a result of that, mass flow rate of condense that is transferred from condenser to cooling tower, has no loss of mass and energy when it returns to condenser. By the way, the mass flow rate of cooling air and power of pump can be calculated.

Evaporator and preheater are the most important heat exchangers that are used to binary systems. The principle of that the heat transfer between geothermal fluid and working fluid is stable and mass conservation or energy conservation is the same as each other. We assumed that the heat exchangers are well insulated so that the heat transfer just occurs between geothermal fluid and working fluid. The flow is constant and continuous, changes of potential and kinetic energies will be neglected (DiPippo 2005).

4. THE DESIGNED MODEL-1

The first model of designed for a typical geothermal source of Turkey is double flash power plant model. Figure 5 shows the model balance of plant (BOP) and power plant flow chart. For this model, two-phase geothermal fluid is flashed from first separator and then steam is getting into the high pressure turbine to generate electricity. The second separator is used to flashing process again for brine with lower pressure.

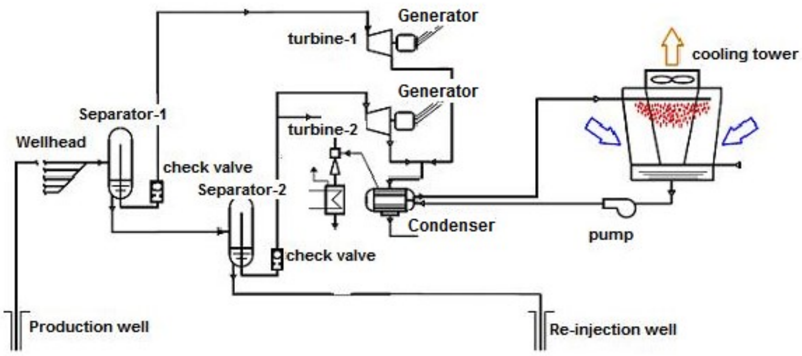

Figure 5: Double flash model flow diagram (Kıvanç 2010).

Each expanding steam are connected the same condenser- cooling tower system. The fluid with reduced temperature from cooling tower, is pressurized by a pump and back to the condenser. After the second separation, geothermal brine is re-injected into the reservoir. Moreover, the jet- ejector pump system is used to remove non-condensable gas, CO_2.

4.1. The Calculation of Optimum Working Conditions for Double- Flash Model

To determine the optimum working conditions of power plant model, turbine output pressure and flashing pressure are calculated.

4.1.1 The Optimization of Turbine Output Pressure

According to this model, since output turbine pressure is under the atmospheric pressure, each of two turbines is connected to the same condenser. As a result, the vacuum pressure values are formed to get more power of turbines. Another parameter of optimization for turbine output pressure is jet- ejector pump system working pressure. The jet-ejector pump system is connected to condenser directly so optimum turbine pressure must provide working ejector system, efficiently. Calculations shows that, the output turbine pressure which is condenser pressure needs to be minimum 0.06 bar value. This pressure value is considered the optimum pressure value of jet-ejector system and turbine- condenser system. Furthermore, the turbine output temperature is affected by the selection of optimum pressure value. Optimum turbine output temperature should have minimum values for cooling system is working efficiently. As a result, the optimum turbine output pressure is calculated 0.06 bar and optimum turbine output temperature is 36 °C.

4.1.2 The Optimization of Separator Pressure

Another important parameter of power plant is separation pressure. For this model, wellhead pressure of selected geothermal source is assumed that 19 bar so the first separator pressure is optimized between 18 bar and 2 bar pressure values and then the second separator pressure is optimized between 17 bar and 0.2 bar pressure values. After the calculation, results are compared to each other and the pressure that provides maximum power of plant is chosen as an optimum separator pressure. Figure 6 shows that the different separator pressures versus the net power of model.

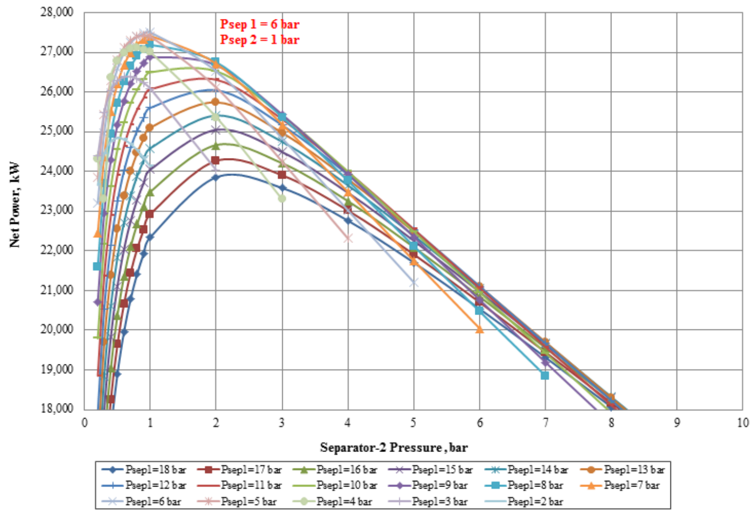

Figure 6: Optimization of separator pressure.

According to Figure 6, if we select the first separator pressure is 6 bar and the second separator pressure is 1 bar, maximum net power of cycle will be; 27.5 MWe. Moreover, graph shows that the net power of model is decreasing with increasing separator pressure values.

Figure 7 shows that changing of high pressure turbine power; low pressure turbine power and net power of cycle depend on the different turbine output pressures.

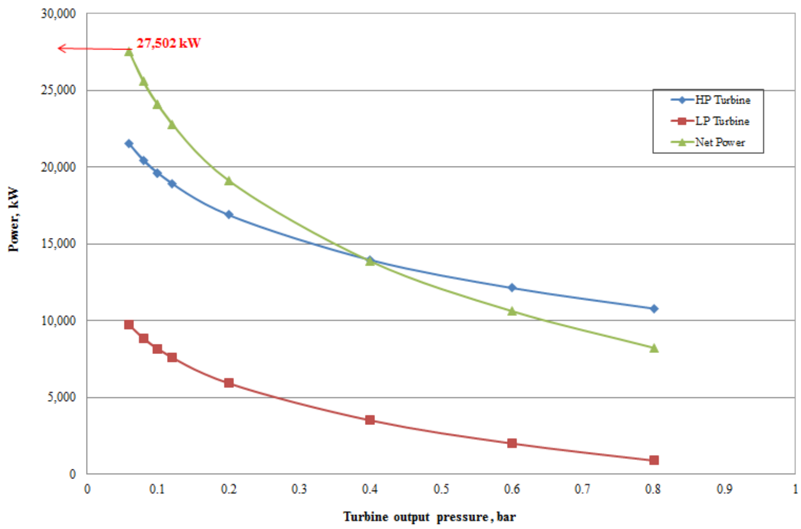

Figure 7: The change of power depends on turbine output pressure.

As a result of optimum working conditions of double flash model, thermodynamic cycle graphs temperature- entropy (T-s) and pressure- enthalpy (P-h) are given below respectively (Figure 8 and Figure 9).

The results of double flash model are 27.5 MWe net power and 10% cycle efficiency.

5. THE MODEL-2 DESIGN

The second model designed for a typical geothermal source of Turkey is bottoming binary power plant one. Figure 10 shows that the model balance of plant (BOP) and power plant flow chart. For this model, two different cycles are integrated. Bottoming binary model includes a single flash system and a binary system that is connected to flash cycle directly. For this study, the working fluid of binary cycle is n-pentane.

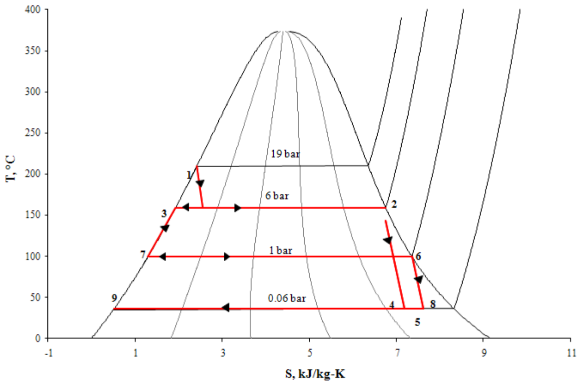

Figure 8: T-s diagram for double flash model.

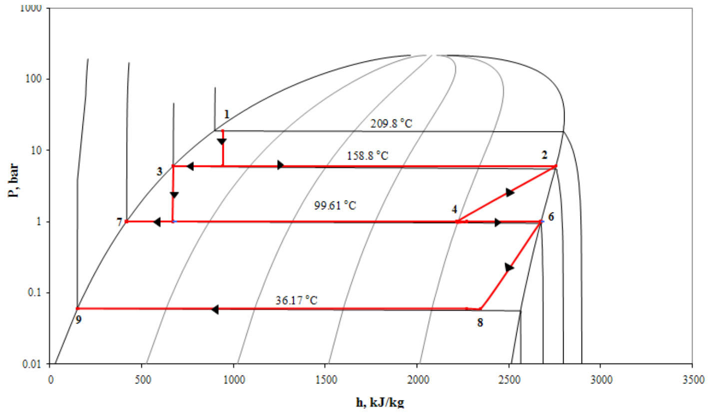

Figure 9: P-h diagram for double flash model.

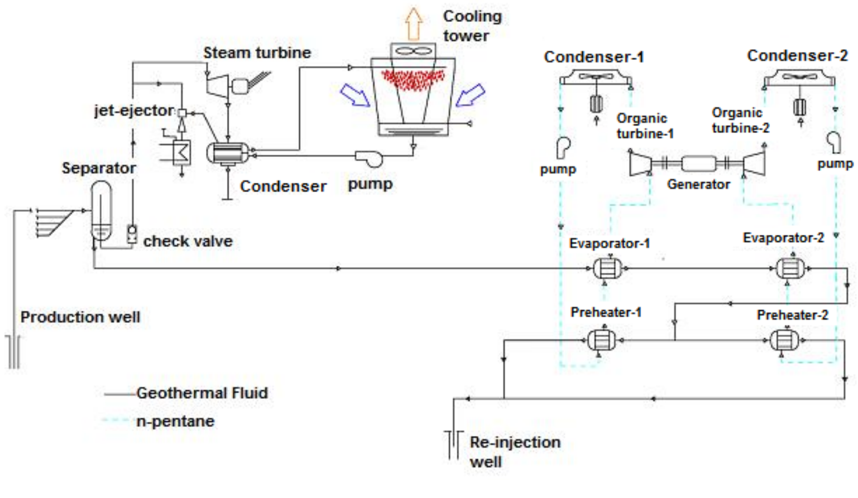

Figure 10: Bottoming binary model flow diagram (Kıvanç 2010).

The first part of this model is single flash system. Production of geothermal fluid flashed from two phases and then steam is forwarded high pressure turbine to generate electricity. After the separation processes, brine goes to binary cycle and its heat energy is transferred to working fluid that is n-pentane. Evaporator and preheater provide saturated vapor conditions of two levels of generating electricity from n-pentane. After the n-pentane becomes saturated vapor in evaporator, expansion process takes place in the turbine to generate electricity (Gökçen and Özcan 2008, Durmuş 2006). Then, n-pentane is condensed with air cooled condenser and it is pressurized by pump to convey it to the preheater. This model includes two binary cycle levels for effective heat transfer and obtaining more energy. After the binary processes, cooled geothermal brine is transferred to re-injection well directly (Kıvanç 2010). During the re-injection process, the temperature of injected brine affects considerably cycle efficiency. The temperature of injected brine is not allowed to drop to the point where silica scaling could become an issue in re-injection wells downstream of it (DiPippo 2005). Because of this situation, in this study, the temperature of re-injection in binary cycle is assumed 80 °C to mitigate scaling problem.

5.1. The Calculation of Optimum Working Conditions for Bottoming Binary Model

To determine the optimum working conditions of second power plant model, separator pressure and organic turbine output pressure are calculated.

5.1.1 The Optimization of Separator Pressure

The separator pressure is an important parameter for optimization of bottoming binary model. Because, if the more brine is obtained after the separation and transferred to the binary cycle, the more power generation will be obtained. For the optimization net power of binary cycle and the temperature of brine coming into binary cycle are compared with different separator pressure values. The separator pressure is assumed values between 16-6 bar and checked against the net power of model depending on changing separator pressure. Figure 11 shows that the change of power of turbines and net power of cycle depending upon the varying separator pressure. It is clear that as the pressure of separator increases, steam turbine power quickly decreases, and in contrast, the organic turbine power increases.

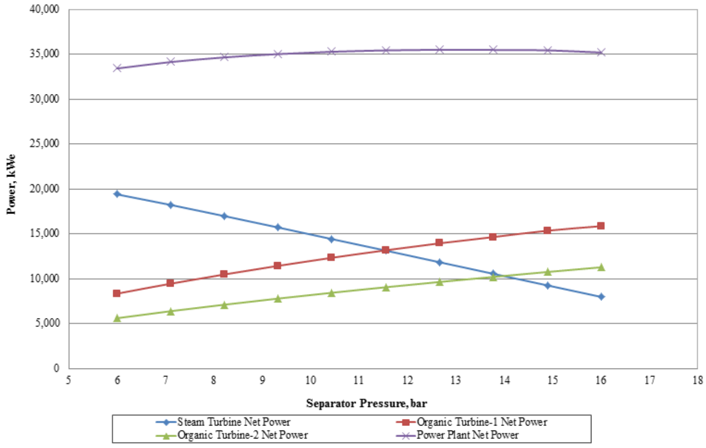

Figure 11: Separator pressure optimization.

As a result of calculation, optimum separator pressure is found 12.67 bara and net power of cycle is 35.5 MWe. After the separation at this pressure value, brine temperature that is entered the binary cycle, will be 190.4 °C.

5.1.2 The Optimization of Organic Turbine Output Pressure

For binary cycle, the optimum output pressure of organic turbine is equal to dew point pressure of working fluid. So, the output temperature of organic turbine should be the dew point temperature of n-pentane that is called 38 °C and the corresponding pressure of dew point at this temperature is 1.09 bara. Each two organic turbine output pressure is assumed 1.09 bara for an optimum turbine pressure.

The optimization of separator pressure and organic turbine pressure, the net power of model is calculated 35.5 MWe and model efficiency is % 12.

Figure 12 and Figure 13 shows that thermodynamic cycle of steam, that are temperature- entropy (T-s) and pressure- enthalpy (P-h) given below respectively.

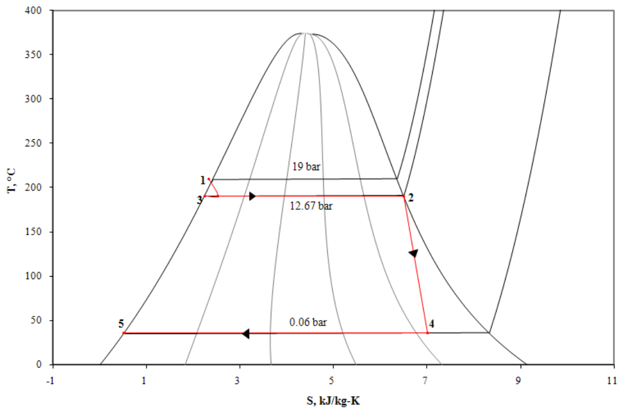

Figure 12: T-s diagram for steam.

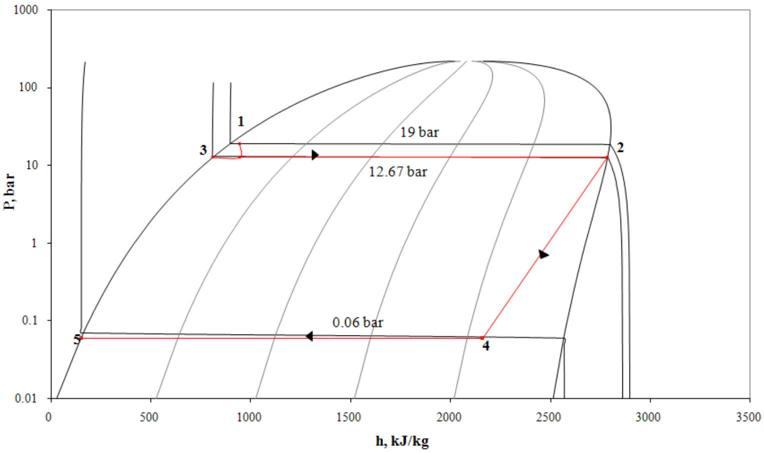

Figure 13: P-h diagram for steam.

The thermodynamic cycle of n-pentane for each two units is drawn. Figure 14 and Figure 15 shows that the first level n-pentane graphs that are temperature- entropy (T-s) and pressure- enthalpy (P-h) given below, respectively. Figure 16 and Figure 17 also shows that second level n-pentane graphs.

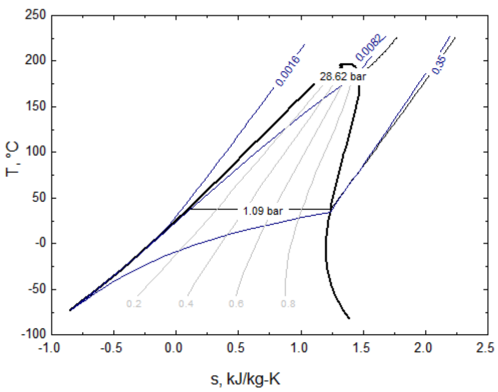

Figure 14: T-s diagram of first level n-pentane.

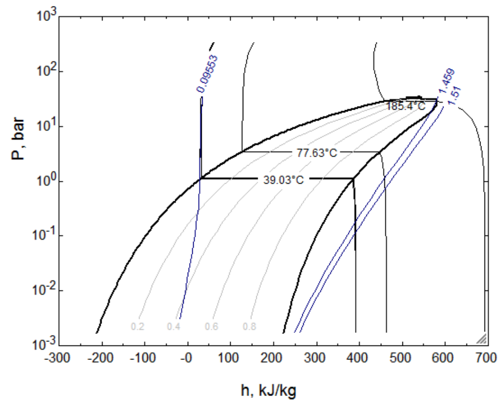

Figure 15: P-h diagram of first level n-pentane.

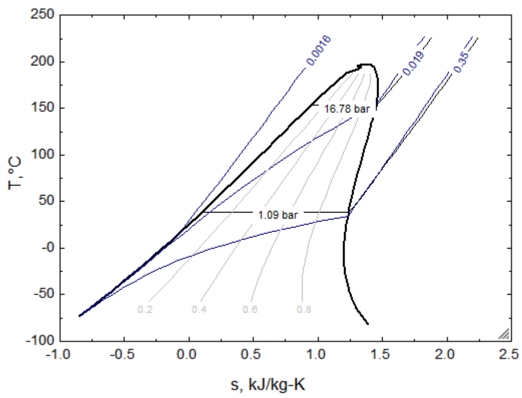

Figure 16: T-s diagram of second level n-pentane.

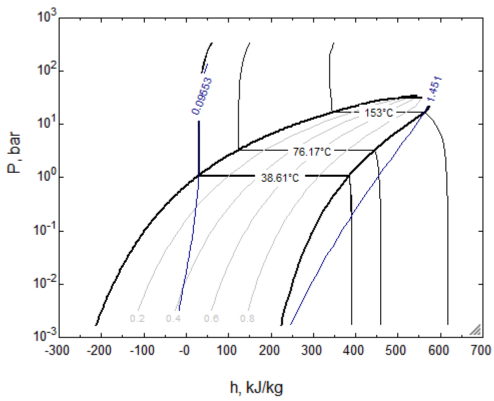

Figure 17: P-h diagram of second level n-pentane.

6. THE MODEL-3 DESIGN

The third model of designed for a typical geothermal source of Turkey is combined power plant model. Figure 18 shows that the model balance of plant (BOP) and power plant flow chart. The main purpose of combined plant model is to generate more power with respect to bottoming binary model is occurred. Combined model includes atmospheric steam turbine and no condenser-cooling tower connection. After the geothermal steam expansion in the atmospheric turbine, exhausted steam is transferred to the second level evaporator directly. Thus, the energy of expanded steam is transferred to the n-pentane in binary cycle more than bottoming binary cycle. This is an important difference between model-2 and model-3.

When heat exchanging is completed between geothermal steam and n-pentane on evaporator-2 and the steam is condensed, CO_2 is flashed away from system as free gas format suitable pressure and temperature conditions (Kıvanç 2010).

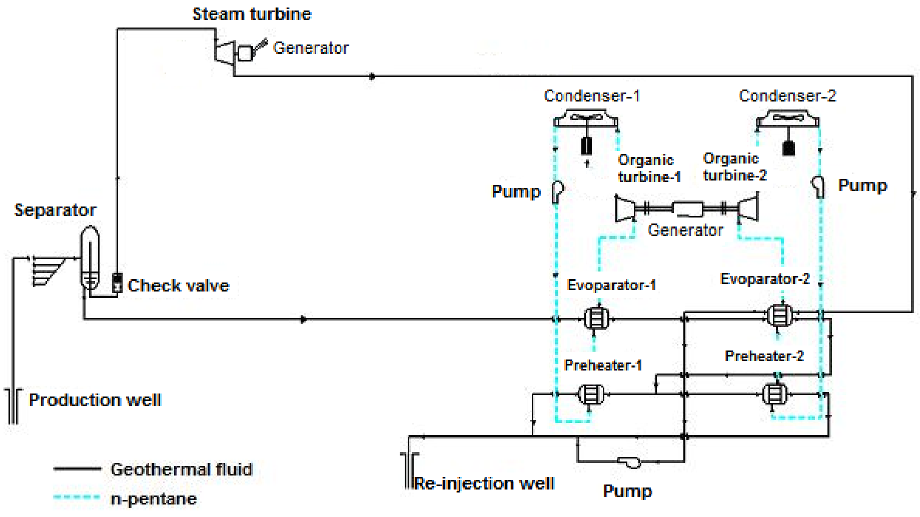

Figure 18: Combined model flow diagram (Kıvanç 2010).

6.1. The Calculation of Optimum Working Conditions for Combined Model

To determine the optimum working conditions of combined power plant model, separator pressure, steam and organic turbine output pressure are calculated.

6.1.1 The Optimization of Separator Pressure

As in the previous two models, the separator pressure is assumed in between 16 bar and 6 bar for optimization and the net power of model is checked against changing separator pressure. Figure 19 shows that the change of turbines power and net power of cycle depending on the varying separator pressure. It is clear that as the pressure of separator increases, steam turbine power and second organic turbine power slightly decreases. But, first organic turbine power increases.

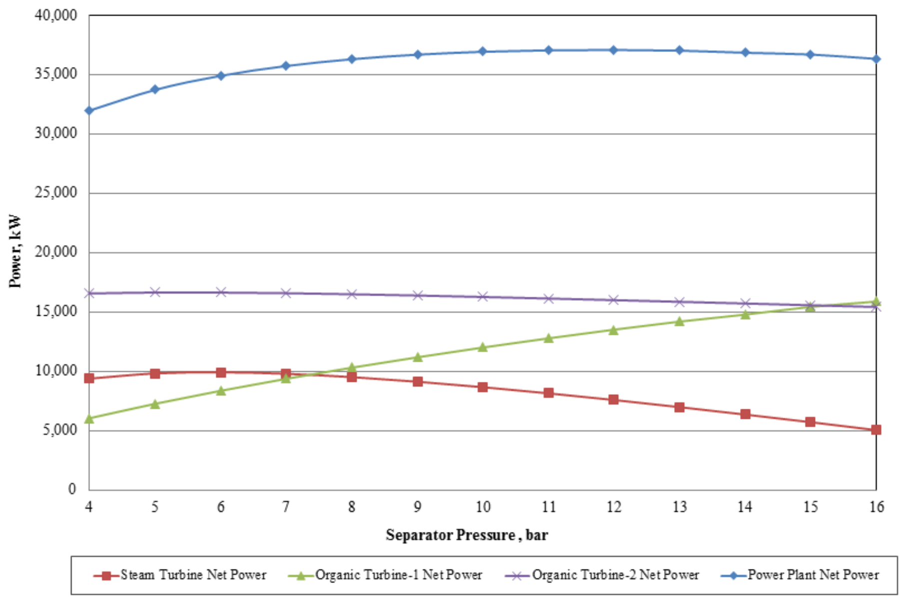

Figure 19: Optimization of separator pressure.

According to all system and comparing solution, the net power of combined cycle is to be maximum value with optimum separator pressure. The optimum separator pressure is calculated 12 bar, net power of cycle is found 37 MWe.

6.1.2 The Optimization of Steam Turbine and Organic Turbine Output Pressure

The type of steam turbine that is used to combined cycle power plant model is an atmospheric turbine. So, the output pressure of steam turbine is atmospheric pressure of the plant region.

The output pressure of organic turbines in binary cycle is to be the dew point pressure of n-pentane as it is in the bottoming binary model.

According to optimized combined cycle model, the net power of cycle is found 37 MWe and cycle efficiency is found % 13.

Figure 20 and Figure 21 shows that thermodynamic cycle of steam in combined model, they are temperature- entropy (T-s) and pressure- enthalpy (P-h) given below, respectively.

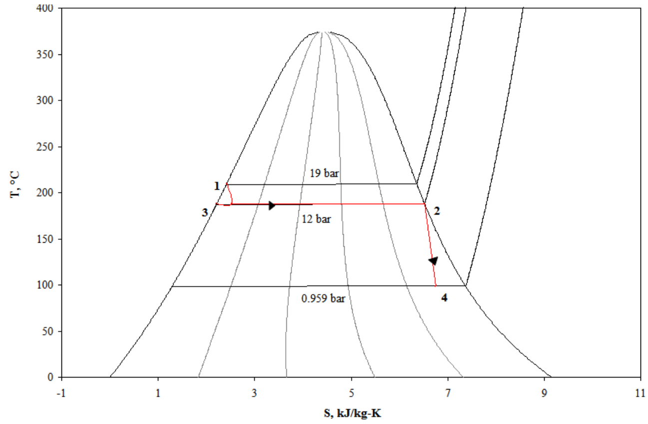

Figure 20: T-s diagram of steam.

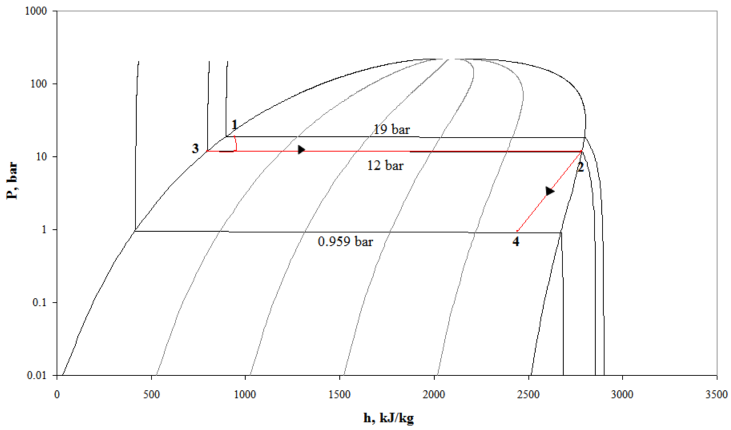

Figure 21: P-h diagram of steam.

Figure 22 and Figure 23 shows that the first level n-pentane graphs, that is, the temperature- entropy (T-s) and pressure- enthalpy (P-h) given below respectively. Figure 24 and Figure 25 also shows that second level n-pentane graphs.

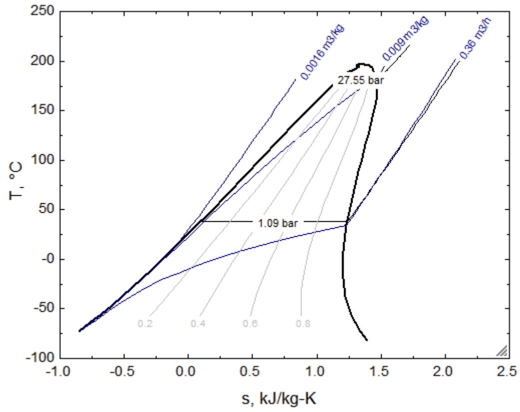

Figure 22: T-s diagram of first level n-pentane.

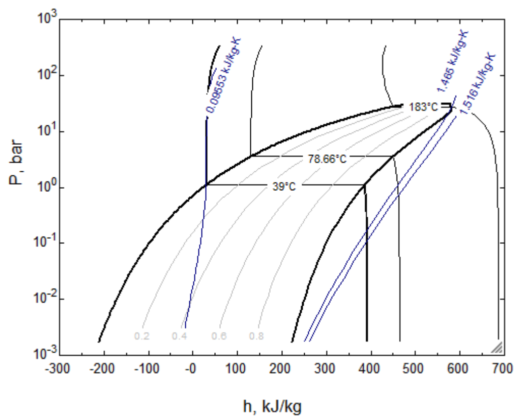

Figure 23: P-h diagram of first level n-pentane.

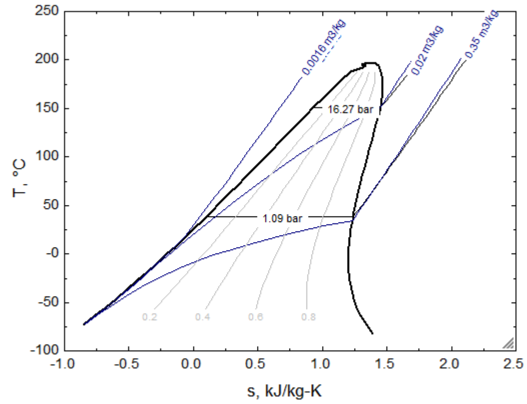

Figure 24: T-s diagram of second level n-pentane.

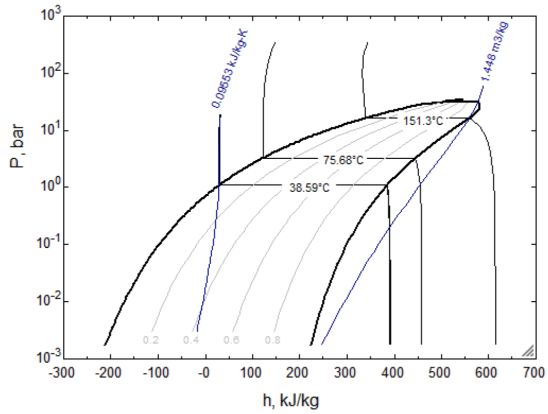

Figure 25: P-h diagram of second level n-pentane.

7. CONCLUSIONS AND RESULTS

The main purpose of this study is to compare three different types of power plant model's power generation capability for typical high enthalpy geothermal source of Turkey.

First, recent power plant technologies are introduced for high enthalpy geothermal sources, and three power plant models are presented. Later, the parameters to use in these models are reported. Then, three different type of power plant model's power generation capacities are calculated using the EES software. These models are double flash, bottoming binary and combined cycle respectively. Finally, for all designed models, plant equipment working conditions are optimized.

To sum up, all model's results are calculated and compared with each other under same conditions. The first double flash model's net power is found as 27.5 MWe; the second bottoming binary model's net power is found as 35.5 and the third combined cycle model's net power is found as 37 MWe, calculated efficiencies as 10%, 12% and 13%, respectively. For all results, the combined cycle model is determined as the best one for this type of geothermal source.

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