PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

Use of Supercritical and Subcritical Binary Models for Geothermal Power Plants and Effects of Geothermal Resource Temperature on Power Plant Design

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Keywords: Supercritical binary model, subcritical binary model, optimum resource temperatures, different working fluids.

ABSTRACT

The power plant technology used for geothermal resources has been continuously developing. Binary power plants designed to generate power especially for middle and low enthalpy geothermal resources are rapidly increasing. In this study, a single stage binary power plant is designed under supercritical and subcritical conditions with different working fluids and then the results are compared. The optimum geothermal resource temperature for binary plants is investigated. The geothermal resource used in all models of this study is water dominated and has high non-condensable gas content. All parameters used in modeling are the same except for geothermal resource temperature. The temperature of geothermal resource is assumed varying between 155°C and 190°C.

Depending on changing geothermal resource temperatures, the results of net powers and thermal efficiencies are compared. At the same time, the effects of subcritical and supercritical working conditions with different working fluid utilized are investigated and their results are presented.

1. INTRODUCTION

The geothermal power plant technologies have been continuously developing depending on their resource properties. Binary power plants, which have been widely used since 2000, have been developed with the aim of increasing power generation mainly from medium and low enthalpy geothermal sources, but they have also been integrated with flash power plants for high enthalpy geothermal sources, enabling more efficient combined plant models to be designed (Kivanc Ates and Serpen, 2016).

The binary power plant technology is mainly separated into two groups according to the working conditions of secondary fluid used. It is possible to obtain more efficient and higher power from geothermal fluids with binary power plant models which can be designed for these working conditions called supercritical and subcritical.

The thermodynamic properties and working conditions of secondary fluids used in binary power plants have a direct impact on generating power of the cycle and plant efficiency. If the working fluid is used under the critical pressure and temperature values, it is called subcritical model or if it is used above critical pressure and temperature values, it is called supercritical model.

In this study, a single stage binary power plant is designed under supercritical and subcritical conditions with different working fluids and then the results are compared. The power plant design and optimization was carried out using EES (Engineering Equation Solver) software.

2. MODEL DESIGN AND ITS PARAMETERS

In this study, a single level binary power plant is designed and the geothermal resource is assumed water dominated with high content of non-condensable gases (NCG). Depending on the resource characteristics, before the geothermal fluid is entered into binary cycle, gas and liquid phases must be separated. While the liquid phase of geothermal fluid, that is brine, is transferred to the first vaporizer of binary cycle the gas phase of geothermal fluid is directly conveyed to the second vaporizer. The power plant design has one heat exchanger group consists of two vaporizer and one pre-heater. Therefore, a recuperator was used at the organic turbine exhaust to be able to recover the power loss in air cooled condenser. The Figure 1 shows that process diagram of designed binary power plant.

For this model, brine goes to heat exchanger group and its heat energy is transferred to working fluid. After the heat exchanging process, low temperature brine and condensate are directly pumped into re-injection well. When the heat exchanging is completed between geothermal steam and working fluid on second vaporizer and the steam is condensed, non-condensable gases are flashed away from system as free gas form at the suitable pressure and temperature conditions (Kivanc Ates and Serpen, 2016).

During the optimization of modeling, geothermal resource temperature, working fluid and its thermodynamic conditions are assumed as changing. All other parameters which are shown in Table 1 are constant for different model optimization studies.

All NCG (non- condensable gases) from geothermal steam is assumed CO_2 and its content by weight in steam is 2%. For model optimization, the temperatures of geothermal resource are assumed to be 155°C, 160°C, 170°C, 180°C and 190°C.

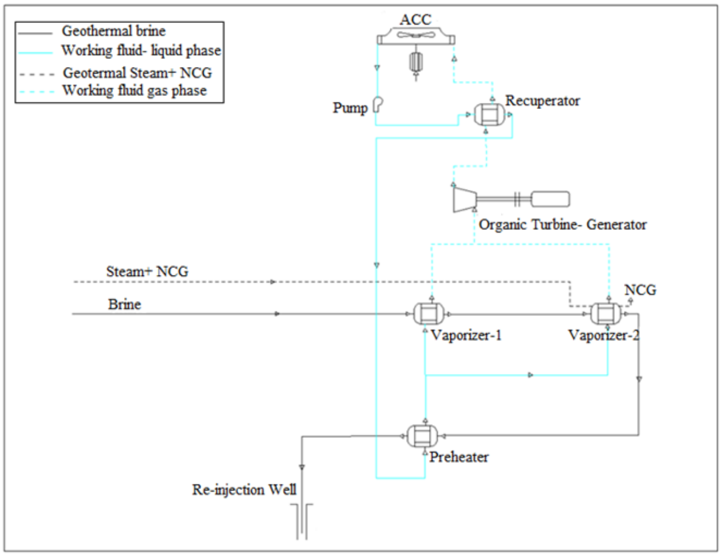

Figure 1: Model Binary power plant flow diagram.

Table 2 shows that the most common working fluids and their thermodynamic properties. Accordingly, n-butane, n-pentane and i-butane are selected as a secondary fluid for subcritical working condition and on the other hand, R134a, n-butane and i-butane are used for supercritical conditions of binary cycle.

Table 1

Constant model parameters

	Unit	Value
Separator Pressure	bar	7
Total flow rate	ton/h	500
Brine/ Steam (+NCG) rate	%	95/5
NCG		CO_2
Organic turbine efficiency	%	85
Generator efficiency	%	98
Pump efficiency	%	80
Cooling tower fan efficiency	%	80
Atmospheric pressure	bar	1.01
Average monthly air temperature	°C	17
Average monthly relative humidity	%	61
Air temperature from the cooling tower exhausted	°C	28
Relative humidity to the air from the cooling tower exhausted	%	90
Re-injection temperature	°C	80

Table 2

Thermodynamic properties of some common working fluids

Fluid	Formula	Critical Temperature, °C	Critical Pressure, bar
Propane	C3H8	96.68	42.47
n-Butane	C4H10	152	37.96
i-Butane	i-C4H10	134.7	36.4
n-Pentane	C5H12	196.5	33.64
i-Pentane	i-C5H12	187.2	33.7
R134a	CH2FCF3	101	40.59

After the working fluid to be used in binary cycle is selected, optimization on some parameters was conducted. The most important optimization parameters in this study are organic turbine inlet and outlet pressure, turbine inlet temperature and pinch temperature of heat exchangers. The place in the heat exchanger where the brine and the working fluid experience the minimum temperature difference is called the pinch point. The value of that difference is designated as the pinch point temperature difference (DiPippo, 2005). The pinch point temperatures of subcritical and supercritical models are different from each other and Table 3 shows these values.

Table 3

Optimization parameters and boundary conditions of models (Augustine, et al, 2009).

Parameters	Subcritical Model	Supercritical Model
Heat exchanger pinch point temperature	5°C- 8°C	5°C- 30°C
Condenser pinch point temperature	≥ 10°C	≥ 10°C
Turbine inlet pressure	$\leq 0.8{*}P_{crt}$	$1.1{*}P_{crt} \leq P_{tin} \leq 1.5{*}P_{crt}$
P_{crt}: critical pressure; P_{tin}: turbine inlet pressure		

For subcritical condition of binary model, the pinch temperature value of heat exchangers is assumed that between 5- 8°C and for supercritical model, these values are between 5-30°C. These pinch temperatures were optimized for different values in between selected boundary conditions. Similarly, the pinch temperature of condenser would be at least 10°C and above in supercritical and subcritical conditions, and at the same time, the working fluid is assumed in saturated liquid phase at the condenser outlet (Augustine, et al, 2009).

The turbine inlet pressure is also optimized between selected boundary conditions that are shown in Table 3. For subcritical conditions, the turbine inlet pressure would be less than 0.8 times of the working fluid critical pressure. For supercritical conditions, different values are used and optimized in the range of 1.1 and 1.5 times of the working fluid critical pressure.

In this study, the analysis of heat exchangers is based on the principle of the heat and mass transfer between geothermal fluid and working fluid which is stable. It is 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 are neglected.

After the optimization for all models, net power and cycle efficiency values are calculated using the following equations.

With the usual assumptions of negligible potential and kinetic energy terms together with steady, adiabatic conditions, the power of turbine is calculated from Equation (1) (DiPippo, 2005).

$$Wt = m_2\,(\mathrm{h}_1 - \mathrm{h}_2) = m_2\eta_t(\mathrm{h}_1 - \mathrm{h}_{2s}) \tag{1}$$

Where W_t is power of turbine (kW), m_2 is the working fluid mass flow rate (kg/s), h_1 and h_2 are enthalpies of inlet and outlet of turbine respectively (kJ/kg), h_{2s} is isentropic expansion enthalpy of turbine and η_t is isentropic turbine efficiency.

The gross electrical power of turbine that will be equal to turbine power times the generator efficiency is given in Equation (2) (DiPippo, 2005).

$$We = Wt\,\eta_{gen} \tag{2}$$

Where W_e is the electrical power of turbine (kW) and η_{gen} is generator efficiency.

The net power of turbine will be equal to gross electrical power of turbine minus all parasitic loads including circulation pump electrical power, condenser fan motor power and non-condensable gas removable system electrical power for flash processes. In this study, expander auxiliaries, control system, heat exchanger efficiencies have been neglected.

For all models in this study, cycle efficiency is defined as thermal efficiency which is based on the first law of thermodynamics. It means that, heat added to the cycle must equal to the net work delivered by the cycle (Kivanc Ates and Serpen, 2016). Thermal efficiency calculation of models is given in Equation (3) and Equation (4) (DiPippo, 2005).

$$\eta_c = \frac{\dot{W}_{net}}{Q_{in}} \tag{3}$$

$$\eta_c = \frac{\dot{W}_{net}}{m_1 C_{fg}(T_{gf} - T_{d0})} \tag{4}$$

Where W_{net} is the net power of cycle (kW), m_1 is mass flow rate of geothermal fluid (kg/s), C_{gf} is specific heat of geothermal fluid (kJ/kg-K), T_{gf} is geothermal fluid temperature (K) and T_{d0} is ambient temperature (K).

3. THE RESULTS OF SUBCRITICAL MODEL

After the optimization of subcritical models with different resource temperature and using different working fluid, the results are illustrated in Table 4.

Table 4

Subcritical Model Results

Resource Temperature, °C	Working Fluid	Gross Power, MWe	Net Power, MWe	Parasitic Load, MWe	Thermal Efficiency, %	Rate of Parasitic Load, %
155	n-butane	4.55	3.64	0.91	6.6	20.00
	n-pentane	6.82	5.99	0.83	10.7	12.17
	i-butane	5.86	4.37	1.49	8.0	25.43
160	n-butane	6.96	5.56	1.40	9.6	20.11
	n-pentane	7.26	6.36	0.90	10.8	12.40
	i-butane	5.34	4.00	1.34	7.0	25.09
170	n-butane	7.02	5.61	1.41	8.9	20.09
	n-pentane	8.81	7.40	1.06	12.1	12.03
	i-butane	4.75	3.46	1.29	5.5	27.16
180	n-butane	7.69	6.04	1.65	8.8	21.46
	n-pentane	9.21	8.06	1.15	11.5	12.49
	i-butane	4.43	3.12	1.31	4.6	29.57
190	n-butane	8.18	6.41	1.77	8.6	21.64
	n-pentane	9.22	8.00	1.22	10.6	13.23
	i-butane	4.57	3.16	1.41	4.3	30.85

Butane, pentane and i-butane are selected as a working fluid for subcritical binary models. Table 4 shows that the gross power, net power, parasitic load, rate of parasitic load and thermal efficiency of power plant depending on different geothermal resource temperature and different working fluids. The parasitic loads include circulation pump and condenser fan motor power, and the rate of parasitic load means that total parasitic load divided by calculated gross power of plant.

According to results, for all geothermal resource temperature, the highest gross power of cycle is calculated with working fluid of pentane. The second highest gross power results are calculated using butane except for 155°C resource temperature.

While under 180°C resource temperature, the gross power of power plant is increasing with increase resource temperature, above the 180°C resource temperature, the gross power and thermal efficiency values are decreasing with increasing resource temperature. Moreover, the rate of increase for net power in between 160°C and 170°C resource temperature is higher than the other resource temperature's results. This rate is calculated 22%. On the other hand, the lowest rate of increase for net power of plant is calculated 4% in between 170°C and 180°C resource temperature.

The increasing resource temperature up to 180°C and above values result in to decreasing net power and thermal efficiency for binary power plant design. These results show that the binary power plant design is optimum between 160°C and 170°C geothermal resource temperature, efficiently.

The Figure 2 shows that the change of net power for different working fluids depends on the resource temperature. As seen in Figure 2, net power of binary plant is increasing with increasing resource temperature for n-pentane and n-butane working fluids. But inversely, if the working fluid is selected i-butane, the net power of power plant is decreasing with increasing resource temperature.

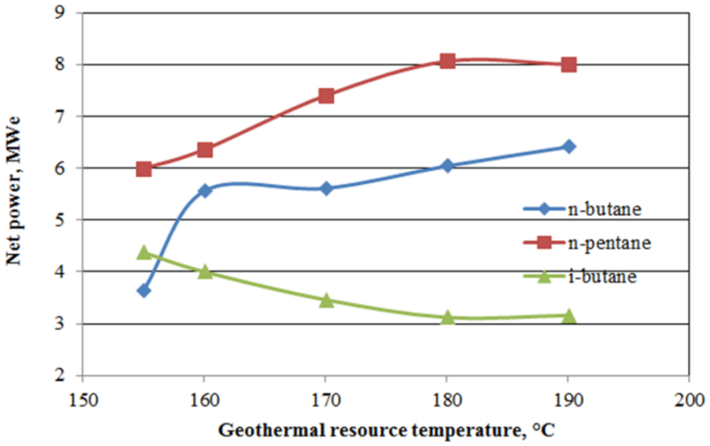

Figure 2: The change of net power for different working fluids according to resource temperature for subcritical models.

Similarly, the calculated thermal efficiencies variation of binary power plant for different working fluids depending on the resource temperature is shown in Figure 3.

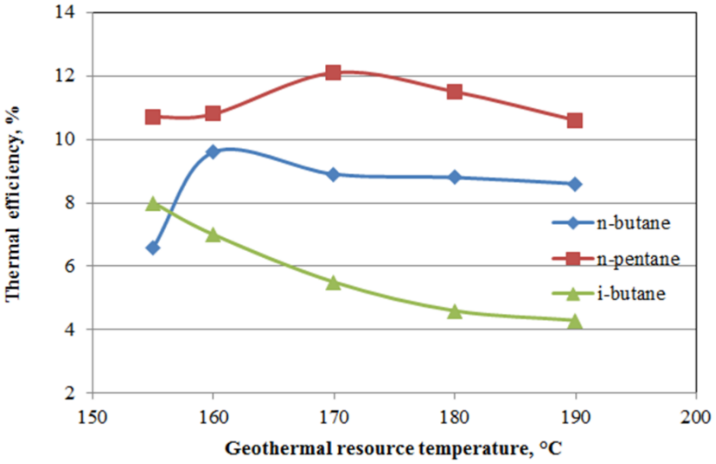

Figure 3: The change of thermal efficiency for different working fluids according to resource temperature for subcritical models.

According to Figure 3, the thermal efficiency is decreasing rapidly for n-pentane and i-butane working fluid with increasing 170°C and above resource temperature. But, for n-butane working fluid, the thermal efficiency of binary power plant has almost constant value with increasing 170°C and above resource temperature values.

4. THE RESULTS OF SUPERCRITICAL MODEL

After studying of supercritical models with different resource temperature and using different working fluids, the results are illustrated in Table 5.

R134a, butane and i-butane are selected as working fluids for supercritical binary models. Table 5 shows the gross power, net power, parasitic load, rate of parasitic load and thermal efficiency of power plants depending on different geothermal resource temperature and different working fluids.

According to supercritical model results, for 155°C and 160°C resource temperature, the highest net power and thermal efficiency values are calculated with i-butane working fluid. When the increasing the resource temperature reaches to 170°C and above, the best results are found with n-butane working fluid. If R134a is selected the working fluid on binary power plant design for supercritical conditions, the net power and thermal efficiency values are the lower than the other results. Moreover, for supercritical models, parasitic loads are higher than the subcritical model results.

The Figure 4 shows that the change of net power for different working fluids depends on the resource temperature. As seen in Figure 4, net power of binary plant is increasing with increasing resource temperature for all working fluids. On the other hand, for R134a results, calculated net power is lower than the other results and the increasing rate of net power in between 160°C and 190°C is very close each other. Conversely, for n-butane and i-butane working fluids, net power increases linearly with increasing resource temperature.

Table 5

Supercritical Model Results

Resource Temperature, °C	Working Fluid	Gross Power, MWe	Net Power, MWe	Parasitic Load, MWe	Thermal Efficiency, %	Rate of Parasitic Load, %
155	R134a	6.09	4.46	1.63	8.2	26.77
	i-butane	8.07	6.12	1.95	11.2	24.16
160	R134a	6.62	4.87	1.75	8.5	26.44
	i-butane	8.55	6.59	1.96	11.5	22.92
170	R134a	6.73	4.88	1.85	7.8	27.49
	n-butane	9.82	7.56	2.26	12.0	23.01
	i-butane	9.39	7.26	2.13	11.5	22.68
180	R134a	6.92	4.99	1.93	7.4	27.89
	n-butane	10.64	8.27	2.37	12.1	22.27
	i-butane	10.16	7.91	2.25	11.5	22.15
190	R134a	7.25	5.08	2.17	7.0	29.93
	n-butane	11.36	8.84	2.52	11.9	22.18
	i-butane	10.77	8.33	2.44	11.2	22.66

Depending on the critical temperature of n-butane, it is not suitable under the 170°C resource temperature. If the resource temperature is above170°C, the highest net power of cycle is calculated with working fluid of n-butane.

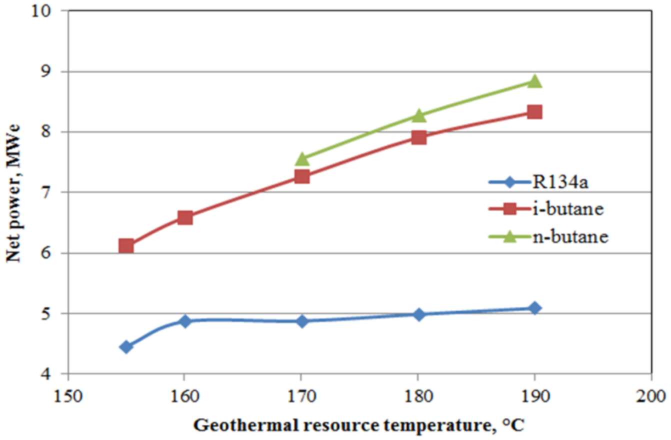

Figure 4: The change of net power for different working fluids according to resource temperature for supercritical models.

Similarly, the calculated thermal efficiencies variation of binary power plant for different working fluid depending on the resource temperature is shown in Figure 5.

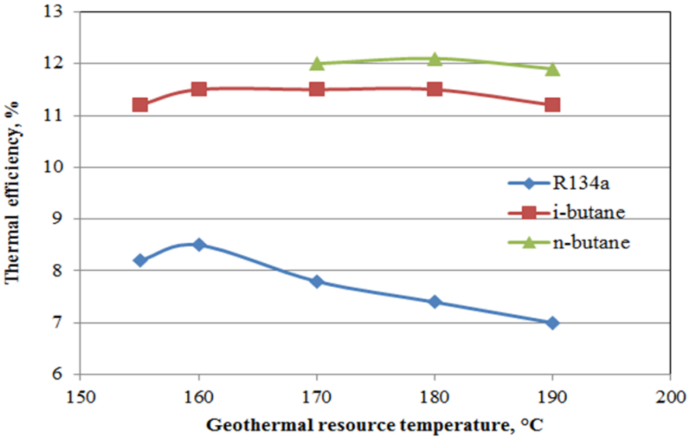

Figure 5: The change of thermal efficiency for different working fluids according to resource temperature for supercritical models.

According to Figure 5, the thermal efficiencies of models are slightly decreasing with increasing resource temperature for i-butane and n-butane working fluids but the rate of decreasing is less than the others for n-butane working fluid. The highest rate of decreasing of thermal efficiency is calculated with R134a working fluid. Depending on the net power and thermal efficiency results, if the geothermal resource temperature is between 170°C and 190°C, n-butane working fluid is the best solution for supercritical conditions. Moreover, if the resource temperature is less than the 170°C, i-butane is very suitable than the R134a for supercritical conditions.

5. CONCLUSION

In this study, the single stage binary power plant is designed and optimized under subcritical and supercritical conditions with different working fluids. The main purpose of this study was to explore how the resource temperature affects the net power and thermal efficiency of binary power plant for supercritical and subcritical working conditions with different secondary fluids.

According to results of subcritical working conditions, the highest net power and thermal efficiency values are calculated with n-pentane working fluid for all resource temperature (8 MWe net powers and 12% efficiency). On the other hand, the lowest net power and thermal efficiency values are calculated with i-butane working fluid (3.12 MWe net powers and 4% efficiency). Another important result of subcritical working conditions, the thermal efficiency is constant or decreasing with increasing resource temperature. The rates of decreasing thermal efficiency of n-pentane and i-butane working fluids are bigger than n-butane results. Moreover, if the resource temperature is between 170°C and 190°C values, the thermal efficiency of binary cycle is nearly constant for n-butane working fluid.

According to results of supercritical working conditions, the highest net power and thermal efficiency values are calculated with n-butane working fluid for the resource temperature in between 170°C and 190°C (8.84 MWe net powers and 12.1% efficiency). Moreover the lowest net power and thermal efficiency values are calculated with R134a working fluid (4.46 MWe net powers and 7% efficiency).

Comparing subcritical and supercritical working conditions, not only the higher parasitic loads are calculated for supercritical models but also their net power and thermal efficiency values are found bigger than the results of subcritical models for different working fluids. In fact, there are much higher net power and efficiencies of supercritical binary models with working the same secondary fluid in literature. However, according to optimization parameters shown in Table 3, the maximum turbine inlet pressure for supercritical model is assumed that 1.5 times critical pressure of working fluid. It is possible to increase the net power and efficiency of supercritical models with increasing turbine inlet pressure but the parasitic loads also increase significantly with increasing turbine inlet pressure for supercritical conditions at the same time. As a result of that, the limit of maximum inlet pressure of organic turbine is selected near the critical pressure of working fluids.

Figure 6 shows that how the maximum net power of binary power plant is changed for subcritical and supercritical working conditions depending on the different resource temperature. As seen in Figure 6, supercritical results are linearly increasing with increasing resource temperature. Although the variation of subcritical net power results is the same as supercritical results trend, it is decreasing with increasing resource temperature over 180°C values.

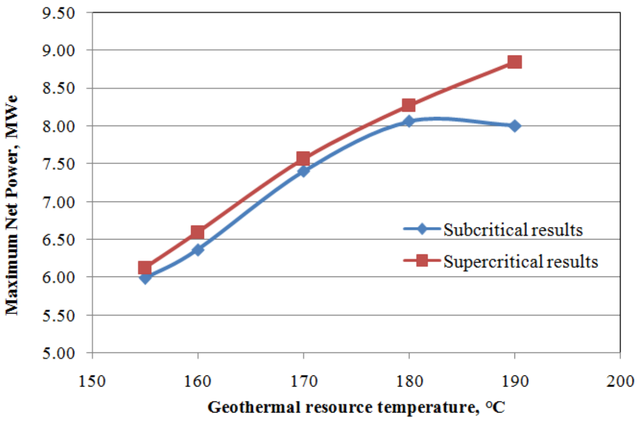

Figure 6: The change of maximum net power for subcritical and supercritical conditions depending on the resource temperatures.

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