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Thermoeconomic Optimization of Geothermal Flash Steam Power Plants

Mehdi Zeyghami

End of Poonak-e-Bakhtari Blvd., Shahrke Ghods, P.O.BOX: 14665/517 Tehran\IRAN

MZeyghami@nri.ac.ir

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ABSTRACT

Flash steam power plants are relatively a common method used to convert the geothermal energy into electricity when production wells produce a mixture of steam and liquid in a geothermal system. In comparison to the single flash system, the double flash steam power plant generates more power from geothermal fluid at the same conditions. However, electricity generation costs are higher for double flash plants. A thermoeconomic optimization model is presented in this paper as the generation costs of single and double flash steam power plants. By considering the pressures in the separator and flash vessel (only in a double flash plant) as the independent variables in the objective function and using numerical search methods (Golden Ratio and Nelder-Mead), the minimum power generation cost was calculated at different geofluid conditions for either single or double flash steam power plants.

The analysis was carried out for plant sizes from 5 to 150 MW. The economy of scale was taken into account for Investment costs and Operation & Maintenance costs. The results for minimum generation cost and net power output using single and double flash geothermal power plants is presented for different geofluid temperatures and flow rates.

1. INTRODUCTION

Geothermal energy is the natural heat energy within the earth. This energy can be recovered in specific areas in hot water or steam. Hydrothermal systems are natural geothermal sources in which water is heated in contact with hot rocks beneath layers of the earth's surface and turns to steam (vapor dominated systems) or hot water (liquid dominated systems) (El-Wakil, 1985). In hydrothermal systems, it is possible to extract the hot geothermal fluid by drilling wells to suitable depths in proper places. The flow could either be natural flow under its own pressure or pumped to the surface.

In liquid dominated systems, pressure drop in the well turns some liquids into vapor, which results in a low quality, two phase mixture at the wellhead. Using flash steam power plants is one of the common ways to convert the extracted heat to mechanical power and electricity. Single flash steam power plants are often the first power plants installed at newly developed liquid dominated geothermal fields (Dipippo 2007). The term “single flash” indicates that geothermal fluid undergoes one flashing process in the system. Flashing is a process of lowering the geofluid pressure below the saturation pressure corresponding to the fluid temperature to transform pressurized liquid to a mixture of liquid and vapor (Dipippo 2007).

In order to achieve a fluid mixture with higher quality and steam flow in the turbine in a single flash power plant, the geothermal fluid is subjected to a constant enthalpy throttling process. After the separation of liquid and vapor phases in a separator, the vapor is used to drive a steam turbine and generate mechanical power. The liquid portion of the flow is reinjected to the source via injection wells.

Due to high temperature and relatively low quality in the separator, the exiting brine has a high flow rate and working potential compared to the steam used to drive the turbine (El-Wakil, 1985). In order to use this wasted energy in a double flash power plant, the liquid exiting the separator is run through a second flashing process (flash vessel and separator). The resulting low pressure steam is sent to a lower stage of the turbine or another steam turbine. At the same geothermal fluid conditions, a double flash steam plant can produce 15-25 % more power output than a single flash steam plant. However, the plant is more complex, more costly, and requires more maintenance (Dipippo 2007).

Flash steam power plants account for a significant share of all geothermal power plants in the world. According to the available data presented by Dipippo (2007), approximately 32% of geothermal plants in the world have a single flash design, and approximately 14% have a double flash design.

In a single flash power plant, separator pressure has a significant effect on the amount of power generated from extracted geothermal fluid and the performance of the cycle. For specific fluid conditions at the wellhead, higher separator pressures (resulting from higher flashing pressure) result in higher pressure steam leaving the separator. Therefore, steam at the turbine inlet would have higher working potential. However, by reducing the flashing pressure (and the dependent separator pressure) increases the mixture quality in the separator, which results in higher steam flow rates at the turbine inlet. However, the specific available energy (exergy) of the steam flow would decline. Thus, separator pressure is a key design parameter in single flash power plants and has a major influence on power generation system performance. In double flash power plants, the flashing pressure should also be considered as an important design parameter. For evaluation of flash steam power plants, design parameters should be selected precisely to achieve the maximum power generation at the lowest generation cost.

The aim of the present work is to introduce a thermoeconomic model for geothermal flash steam power plants. Optimization of design parameters for single and double flash power plants based on this model makes it possible to compare utilization of these plants in similar conditions. To achieve this goal, net power output from flash steam power plants was calculated at different geofluid temperatures by using thermodynamic equilibriums and cycle specifications. After considering economic factors, the thermoeconomic objective function was defined as the generation cost of the plant. Then, the appropriate design variable values that minimized the objective function were calculated by means of a numerical search method. Analyzing the results made it possible to compare geothermal flash power plants in different conditions. The analysis considered a power capacity range of 5 to 150 MW.

2. THERMODYNAMIC ANALYSIS

2.1 Single Flash System

A schematic of a typical single flash power plant is shown in Figure 1, and a T-s diagram of the cycle is presented in Figure 2. As hot brine (1) flows through the well in the geothermal source, it experiences a constant enthalpy pressure drop. This process is an adiabatic throttling which results in a low quality saturated mixture at the wellhead. The flow is throttled further in a flash separator resulting in a slightly higher quality mixture in the separator (2), where the fluid is separated into dry vapor (3) and saturated liquid (4) components. The latter is reinjected to the ground. Dry steam, which is a small fraction of the total entering geothermal fluid flow to the plant, is expanded in the turbine (5) to generate electricity. Exhaust steam from the turbine is mixed with cooling water from the cooling tower (8) in a direct contact condenser. The condenser outlet is saturated liquid (6). The majority of this effluent is pumped to the cooling tower (7), and the rest is reinjected into the ground. The fluid in the cooling tower loses heat (8) and enters the condenser to mix with the turbine exhaust flow.

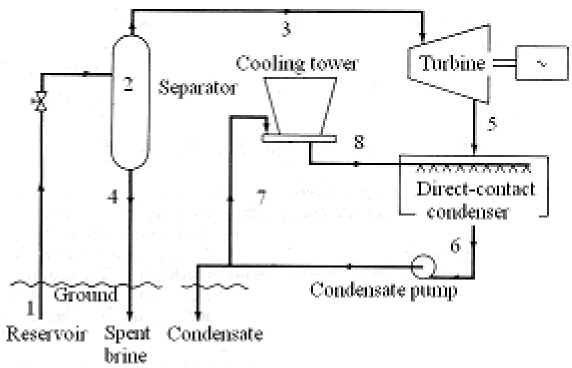

Figure 1. Simplified schematic of flow diagram for a single flash power plant

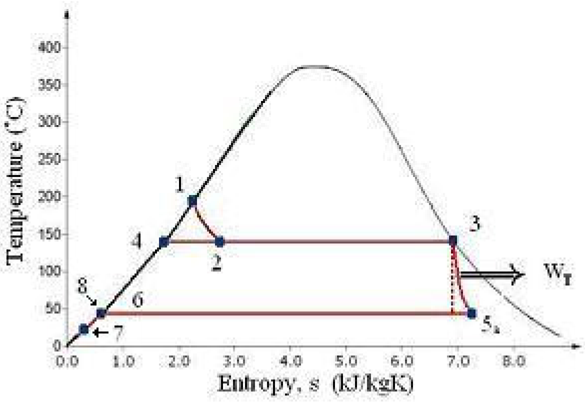

Figure 2. Temperature-entropy diagram for a single flash power plant

Evaluation methods of working fluid conditions in different locations of the cycle by means of mass and energy conservation laws and thermodynamic properties of geothermal fluid are presented by Dipippo (2007) and won't be repeated in this paper. A simulation code has been developed in Visual Basic to carry out the needed calculations with high accuracy in a short time. If fluid conditions in the different points of the cycle are known, it is easy to calculate the performance characteristics of the plant.

The gross power produced by the turbine is calculated according to Equation 1

$$W_{T.S} = m_S(3)\times[h_S(3)-h_S(5)] \quad (1)$$

where m is the mass flow rate of the working fluid, h is its enthalpy, and the S subscript denotes a single flash system. The parasitic power requirements have been assumed to be 5% of the gross turbine power:

$$W_{net.S} = 0.95\times W_{T.S} \quad (2)$$

Geothermal plants using flashed steam do not operate on a cycle, but involve a series of energy conversion processes. A thermodynamically valid basis for comparing the thermodynamic excellence of geothermal energy conversion processes is provided by the Utilization Factor. The utilization factor is defined as the ratio of net output work to the ideal work available from the geofluid between its initial state and the sink condition (lowest temperature for heat rejection) [3]. The utilization factor for a single flash power plant can be expressed in Equation 4, and the ideal available work is given in Equation 5

$$UF_S = \frac{W_{net.S}}{E_{in.S}} \quad (3)$$

$$E_{in.S} = m_S(1)\times [(h_S(1)-h_0)-T_0(s_S(1)-s_0)] \quad (4)$$

Where $E_{in,S}$ is the maximum available work of fluid at the conditions of the geothermal source, T_0 is the available heat sink temperature, and h_0 and s_0 are the enthalpy and entropy of the fluid at ambient pressure and temperature, respectively.

It is assumed that fluid conditions at the wellhead are those of a saturated liquid. Hence, by knowing the geofluid's flow rate and temperature at this point, the thermodynamic state of the flow is also known. The condensing pressure (at point 5) depends on cooling media characteristics and the design of the cooling tower. A lower condensing pressure results in a higher utilization factor. Because the target of this study is the comparison of single and double flash steam power plants at similar conditions, the condensing pressure is assumed to be constant at 12.3 kPa for both systems. The only remaining design variable is the separator pressure.

If the goal of the optimization procedure was to obtain the highest utilization factor, the net power output of the cycle would be the proper objective function to be optimized (maximized in this case). However, considering the generation cost of the plant as the objective function makes it possible to analyze these two systems from an economic viewpoint.

2.2 Double Flash System

A schematic of a double flash power plant and its T-s diagram are given in Figures 3 and 4, respectively. In a double flash power plant, brine flows from the separator (4) to a flash vessel, which is a secondary low pressure separator. In the flash vessel (5), saturated liquid is re-flashed at lower pressure, and the steam portion of the flow is admitted to a lower stage of the turbine. Remaining liquid from the flash vessel (7) is reinjected into the ground. The rest of the cycle is the same as a single flash power plant. The exiting brine from the plant has lower available energy, resulting in reduced losses in the energy conversion process.

Using thermodynamic equilibriums and the conservation laws of mass and energy, Dipippo (2007) has declared the calculation method for the analysis of fluid characteristics in different parts of the plant. This subject won't be discussed further in this paper. Considering fluid conditions at different points of the system as known parameters, it is possible to calculate the performance characteristics of the plant.

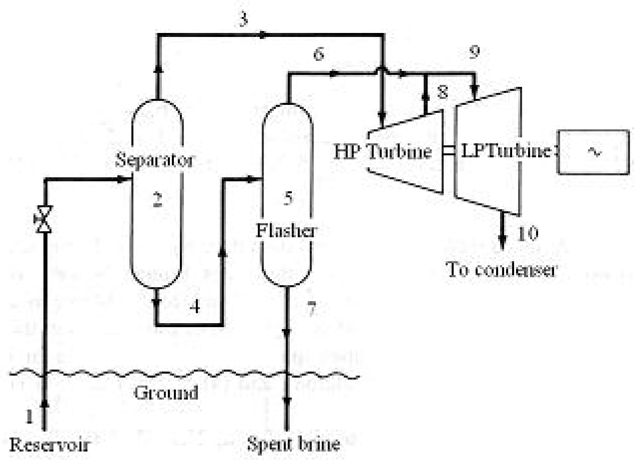

Figure 3. Simplified schematic flow diagram for a double flash power plant

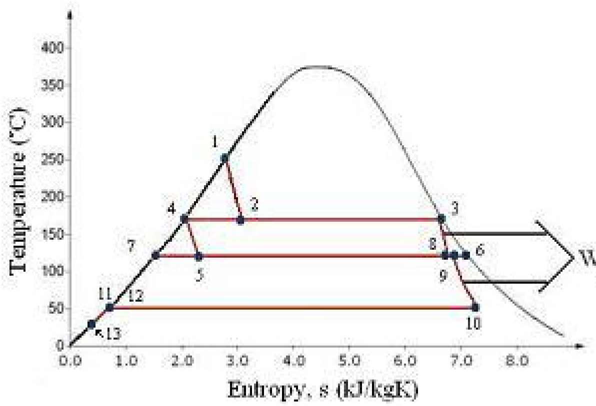

Figure 4. Temperature-entropy diagram for a double flash power plant

Assuming 5% parasitic power requirements, the gross power from steam turbine and the net generated power from the plant by are given in Equations 5 and 6 (Note: the D subscript denotes a double flash system):

$$W_{T.D} = m_D(3)\times[h_D(3)-h_D(8)]+ m_D(9)\times[h_D(9)-h_D(10)] \quad (5)$$

$$W_{net.D} = 0.95\times[W_{T.D}] \quad (6)$$

The utilization factor for a double flash power plant is expressed in Equation 7:

$$UF_D = \frac{W_{net.D}}{E_{in.D}} \quad (7)$$

$$E_{in.D} = m_D(1)\times [(h_D(1)-h_0)-T_0(s_D(1)-s_0)] \quad (8)$$

Similar to the single flash system, it is assumed that the fluid conditions at the wellhead are those of a saturated liquid, and the condensing pressure is considered to be constant at 12.3 kPa. Therefore, the only remaining design variables are the separator pressure and the flash vessel pressure.

2. THERMOECONOMIC OBJECTIVE FUNCTION

In order to compare the utilization of single and double flash power plants to generate power from a geothermal field, the thermodynamic objective function has been established to be the generation cost of the plant. The generation cost function is the total annual cost of the plant divided by the mean annual energy output of the power plant. The aim of the optimization procedure is to minimize the objective function for each system. The generation cost is given in Equation 9:

$$GF = \frac{C_{Tot}}{W_{net}\times H} \quad (9)$$

where W_{net} and H are the mean annual output of the plant and the plant working hours each year. C_{Tot} is the total annualized cost of the plant, which includes the amortized investment cost and annual Operation & Maintenance costs, as shown in Equation 10:

$$C_{Tot} = C_A + C_{O\&M} \quad (10)$$

For calculating power generation cost, the economy of scale was considered (i.e. larger production capacities are less expensive per kW than smaller ones). Based on the work of Sanyal (2005), the specific O&M costs for geothermal power plants approximately range from 2.0 US¢/kWh for a 5 MW plant to 1.4 US¢/kWh for a 150 MW plant. Assuming an exponential decline in specific O&M cost ($c_{o\&m}$) in US¢/kWh with plant capacity (P) in MW, we have:

$$c_{o\&m} = 2.0\times e^{-0.0025(P-5)} \quad (11)$$

And the annual O&M cost is:

$$C_{O\&M} = c_{o\&m}\times W_{net}\times H \quad (12)$$

Based on information presented by Enthingh and McVeigh (2003), the specific investment cost for steam flash geothermal power plants is estimated to vary from 1200 US$/kWh to 1800 US$/kWh for single flash power plants and 1500 US$/kWh to 2400 US$/kWh for double flash power plants, depending on the project size and other project specific criteria.

The higher-end costs correspond to the smallest plant size (5 MW), and the lower-end costs correspond to the largest plant size (150 MW) for both systems. According to the work of Sanyal (2005), these costs are slightly underestimated. As the objective of present work is the comparison of two systems in different situations, the cost values can be considered accurate enough. The presented investment cost values include the cost of the entire geothermal project (i.e. initial wells, power plant equipments, etc.). In this study, the costs of power plant equipment are considered separate from other associated costs. According to Hance (2005), the costs of the power plant and geofluid gathering system form 65% of total project costs. Therefore, the specific investment cost is considered to be 1170 US$/kWh for a 5 MW single flash power plant and 1560 US$/kWh for a 5 MW double flash power plant. The specific investment cost is considered to be 975 US$/kWh for a 150 MW single flash and 780 US$/kWh for a 150 MW double flash. Within the above values, the costs of power plants would follow an exponentially declining curve as the capacity of the plant increases. The specific investment costs of the single and double flash power plants are given in Equations 13 and 14, respectively:

$$c_{I.S} = 0.65 \times 1800 \times e^{-0.0028(P-5)} \tag{13}$$

$$c_{I.D} = 0.65 \times 2400 \times e^{-0.00324(P-5)} \tag{14}$$

Where $c_{I,S}$ and $c_{I,D}$ are in US$/kW. The investment cost for either system is given in Equation 15:

$$C_I = c_I \times P_R \tag{15}$$

Where P_R is the rated plant capacity in kW. The amortized investment cost is needed in these calculations. Therefore, the investment cost should be considered as equal amounts of money transactions in the project lifetime, as shown in Equation 16:

$$C_A = C_I \times CRF \tag{16}$$

Where CRF is the capital recovery factor given in Equation 17:

$$CRF = \frac{i \times (1+i)^N}{(1+i)^N - 1} \tag{17}$$

Where N and i are project lifetime and effective discount rate.

4. LAYOUT OF THE OPTIMIZATION PROCESS

The solution of every optimization problem involves the selection of the design variables, objective function, and constraints of the problem (Valdes et al, 2003). The objective function is presented in the previous section. Optimization variables are the independent design variables of each system. In single flash systems, separator pressure is considered as the design variable and in double flash systems, the pressures of the separator and flash vessel are the design variables. Other parameters are constant in both systems.

The ranges of variations in design variables should be defined carefully, so that they can not take values that make the system parameters physically unacceptable. In a flash power plant, separator pressure can not be higher than fluid pressure at the well which is $P_S(1)$ in the single flash system and $P_D(1)$ in the double flash system (S and D subscripts denote single and double flash). The flash vessel pressure can not be higher than the separator pressure in the double flash power pant design. Also, the pressures in the separator and flash vessel can not fall under atmospheric pressure, which is considered to be 100 kPa, as shown in Equations 18 and 19.

$$100 \le P_{S,Seperator} < P_S(1) \tag{18}$$

$$100 \le P_{D,Flasher} < P_{D,Seperator} < P_D(1) \tag{19}$$

It is also assumed that the geothermal fluid flow rate (well productivity) has no effect on the pressure at the wellhead, and these two parameters are independent of each other. Also, the pressure losses in pipelines and other equipment are considered to be negligible.

A parametric study, or running the simulation code while repeatedly introducing suitable changes, may be carried out to find the values of variables that minimize the objective function. However, this approach is very time consuming. Using an optimization technique is a more efficient way to assess the effect of design modifications in a direct way. There are several techniques to complete the optimization process, including numerical search methods (Mathews 1987). In order to carry out single flash optimization in the present work, the golden ratio search method was used. The Nelder-Mead optimization method, which is a modified simplex search method for finding minimum of N variable functions, was used to optimize double flash power system.

4. RESULTS

The calculations rely on accurate properties of geothermal fluid, here assumed to be pure water. Thus, normal steam tables from Van Wylen et al 1993) were used to find the thermodynamic properties of the working fluid in power plant cycles. The main features of geothermal flash steam plans considered for present work are shown in Table 1.

Table 1. Main features considered for flash steam plants

Effective discount rate [%]	10
Annual working hours[hr]	7000
Plant lifetime[yr]	20
Turbine isentropic efficiency*[%]	85
Condenser temperature[ºC]	50
* In the calculation process turbine efficiency is down grade to account for moisture in the lowest pressure stage using Bauman rule (Dipippo 2007)	

Calculations for single and double flash plants with a geothermal fluid flow of 100 kg/s at 200ºC have been carried out as the base point. For each plant, the fluid characteristics in different parts of the system that would result in the lowest generation cost has been calculated. The results for a single flash power plant are shown in Table 2, considering points as they were named in Figure 1. The same results for the optimized double flash plant are presented in Table 3.

Double flash plant power generation capacity is 63.96 kW per unit geothermal flow rate entering the power plant at 200 ºC (with a 38.44% utilization factor). Power generation capacity from a single flash power plant in the same conditions will be 51.24 kW (with 31.58% utilization factor) per unit geofluid flow. The results indicate that double flash plants generate 24.82% more power than a single flash plant in this situation. However, the generation cost is 4.6 US¢/kWh for a double flash plant and 3.96 US¢/kWh for a single flash plant. Thus, the generation cost is 16.2% higher in double flash power plants.

For the same geofluid temperature, the separator and flash pressures and required flow rates from the field for 5, 50 and 150 MW power generation capacity are shown in Table 4 for both single and double flash systems.

Table 2. Working fluid characteristics for optimized single flash plant

	P [kPa]	T [°C]	h [kJ/kg]	s [kJ/kgK]	Flow rate [kg/s]	x [%]
Point 1	1553.8	200	852.43	2.3308	100	Saturated Liquid
Point 2	198.6	120	852.43	2.4144	100	15.5
Point 3	198.6	120	2706.31	7.1294	15.83	Saturated Steam
Point 4	198.6	120	503.74	1.5276	84.17	Saturated Liquid
Point 5	12.3	50	2365.62	7.3773	15.83	90.3
Point 6	12.3	50	208.94	0.7025	426.15	Saturated Liquid
Point 7	12.3	50	208.94	0.7025	410.32	Saturated Liquid
Point 8	12.3	30	125.73	0.4345	410.32	Subcooled Liquid

Table 3. Working fluid characteristics for optimized double flash plant

	P [kPa]	T [°C]	h [kJ/kg]	s [kJ/kgK]	Flow rate [kg/s]	x [%]
Point 1	1553.8	200	852.43	2.3308	100	Saturated Liquid
Point 2	631.6	160.9	852.43	2.3502	100	10.1
Point 3	631.6	160.9	2759.04	6.7428	8.33	Saturated Steam
Point 4	631.6	160.9	679.27	1.9512	91.67	Saturated Liquid
Point 5	100.7	99.8	679.27	2.0045	91.67	9.1
Point 6	100.7	99.8	2682.03	7.3571	10.6	Saturated Steam
Point 7	100.7	99.8	418.2	1.3046	81.07	Saturated Liquid
Point 8	100.7	99.8	2503.59	6.8956	8.33	93.8
Point 9	100.7	99.8	2600.01	7.1541	18.93	96.6
Point 10	12.3	50	2365.69	7.3497	18.93	89.7
Point 11	12.3	50	208.94	0.7025	507.47	Saturated Liquid
Point 12	12.3	50	208.94	0.7025	488.54	Saturated Liquid
Point 13	12.3	30	125.73	0.4345	488.54	Sub cooled Liquid

Table 4. Results for optimized single and double flash plants

Energy conversion system	Geofluid temp. [°C]	Separator pressure [kPa]	Flasher pressure [kPa]	Mass flow rate [kg/s] needed for			Generation cost [US¢/kWh]		
				5 MW	50 MW	150 MW	5 MW	50 MW	150 MW
Single flash	200	198.6	N.A.	97.58	975.9	2927.5	3.963	3.43	2.700
Double flash	200	631.6	100.7	78.18	768.9	2305.6	4.618	4.050	3.028

For the same geofluid temperature, the separator and flash pressures and required flow rates from the field for 5, 50 and 150 MW power generation capacity are shown in Table 4 for both single and double flash systems.

The minimum generation cost of a single flash power plant at different geofluid temperatures are shown in Figure 5, and flow rates and the correspondent net power output for each point are in shown in Figure 6. The generation cost varies from 5.84 to 2.70 US¢/kWh, and the plant capacity varies from 5 to 150 MW.

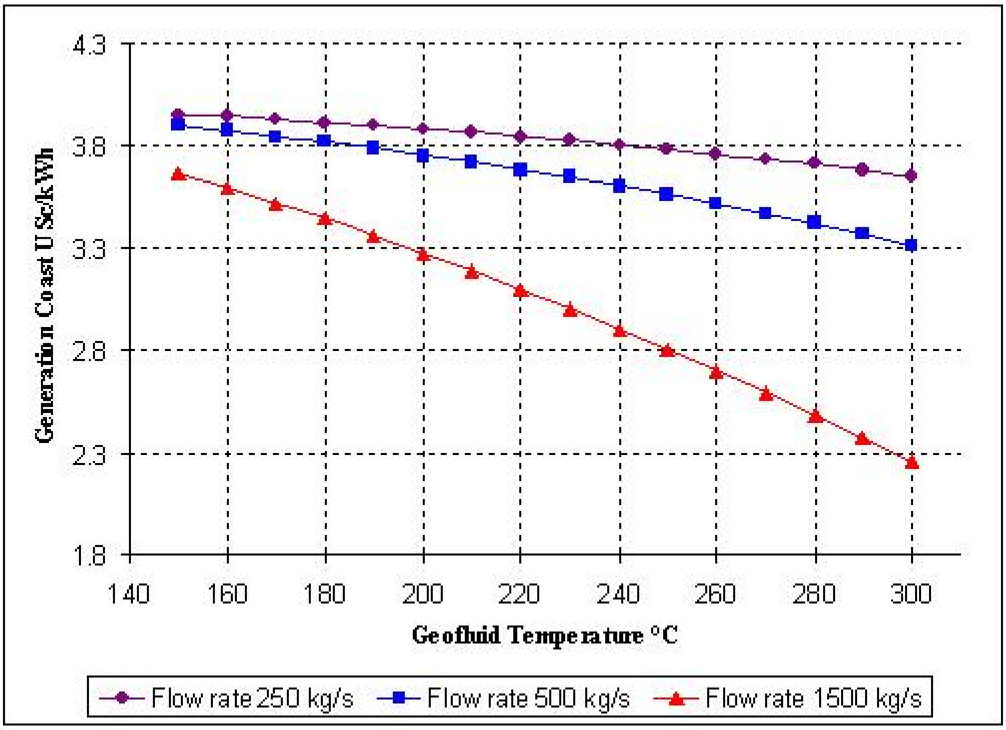

Figure 5. Minimum generation costs for a single flash plant at different geofluid temperatures and geofluid flow rates of 250, 500, 1500 kg/s

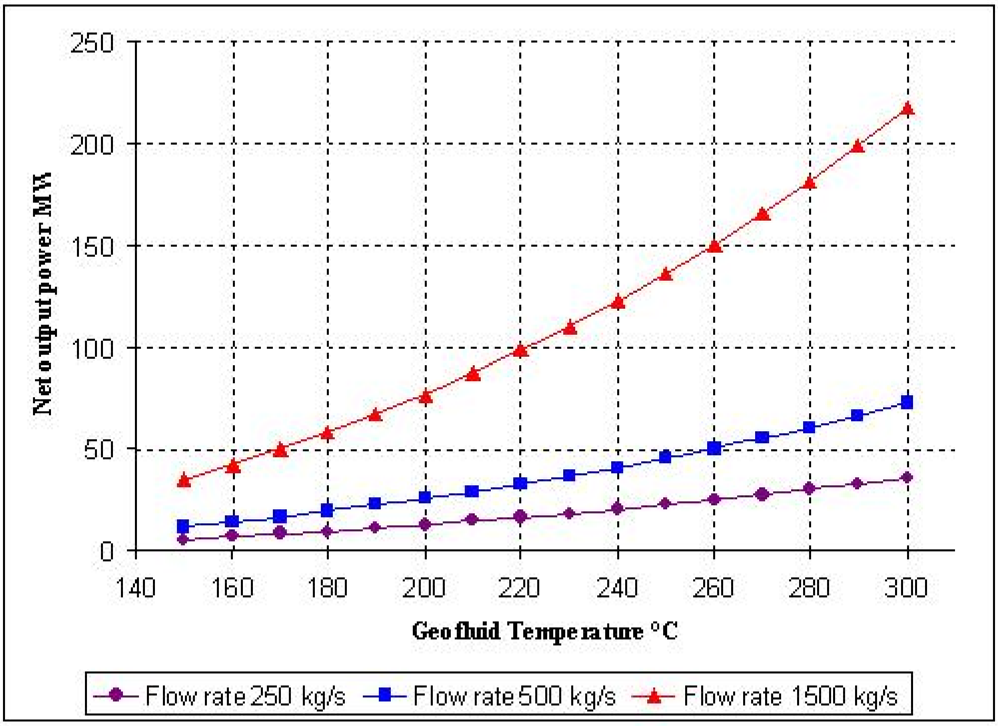

Figure 6. Net power output for thermoeconimic optimized single flash plant at different geofluid temperatures and geofluid flow rates of 250, 500, 1500 kg/s

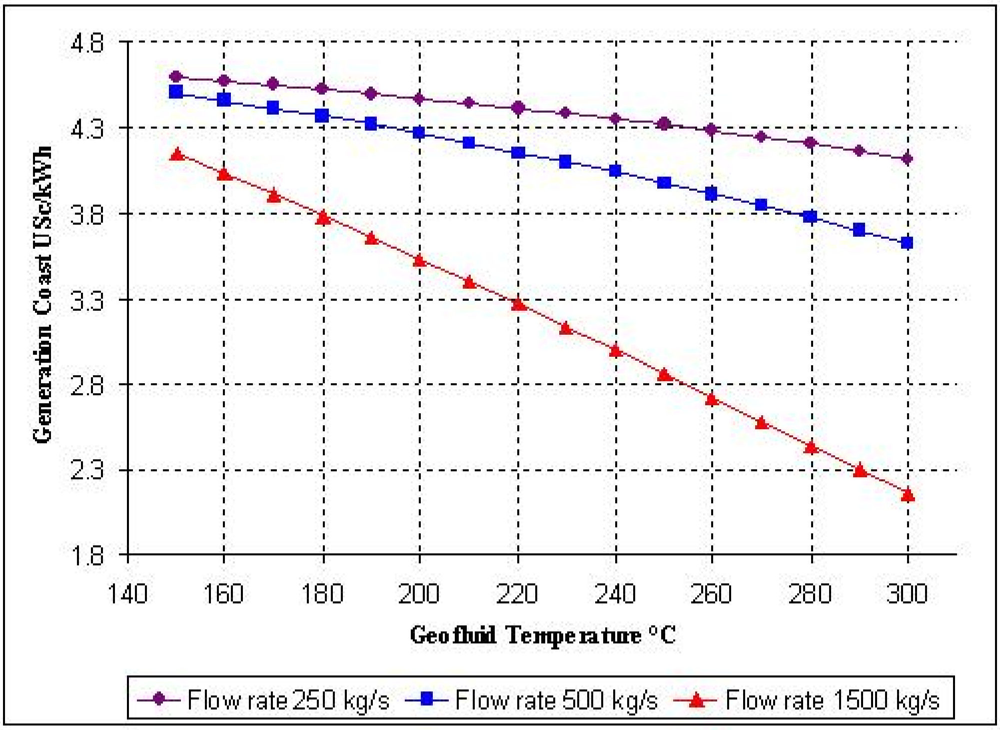

Figure 7. Minimum generation cost for a double flash plant at different geofluid temperatures and geofluid flow rates of 250, 500, 1500 kg/s

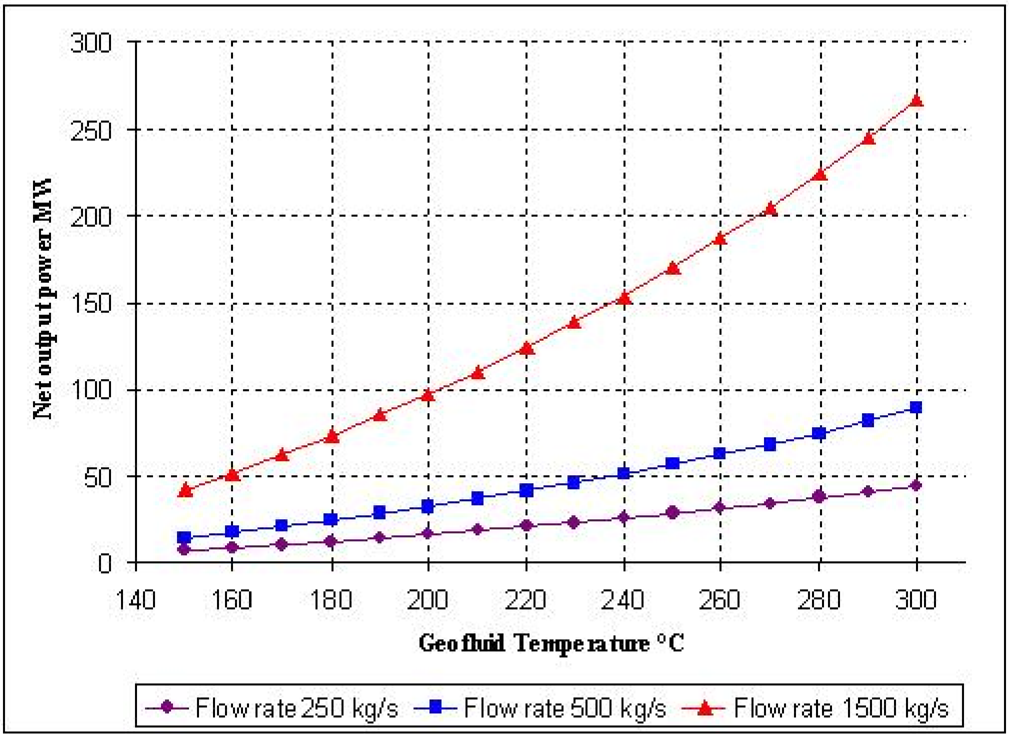

Figure 8. Net power output for thermoeconimic optimized double flash plant at different geofluid temperatures and geofluid flow rates of 250, 500, 1500 kg/s

The corresponding results for double flash power plants are shown in Figures 7 and 8. When the net power output increases from 5 MW to 150 MW, the minimum generation cost declines from 4.59 to 3.00 US¢/kWh.

6. CONCLUSIONS

1. At the same geofluid conditions, using a double flash plant instead of single flash design results in higher plant capacity (between 19% - 26%), which increases as the available energy from the geofluid gets higher.

2. Double flash power plant has higher generation costs than single flash plants at the same capacity. The generation cost difference between the two systems gets lower as the capacity gets higher. This difference decreases from 16.2% for 5 MW plants to 11.1% for 150 MW plants.

3. By increasing the plant capacity in both systems, the generation cost declines. For single flash plants, increasing the plant capacity from 5 MW to 150 MW reduces generation cost from 3.95 US¢/kWh to 2.7 US¢/kWh. For double flash plants, increasing the capacity of the plant from 5 MW to 150 MW causes generation cost decline from 4.54 US¢/kWh to 3.00 US¢/kWh

4. For an entire geothermal plant, if the initial well development and make up well drilling are taken into account, the total generation cost difference between double and single flash plants declines, and it is possible that double flash plants become cheaper due to fewer wells needed in double flash plants (because less geofluid is required per kW capacity, as shown in Table 4).

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