

Modeling and Optimization of Possible Bottoming Units for General Single Flash Geothermal Power Plants

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ABSTRACT

When utilizing geothermal fields for power production, a single flash power plant is often the initial plant to be built. In most cases, a considerable amount of hot brine is wasted when using single flash plants, but the energy from this brine could be utilized for additional power generation. This study was performed to find for a fast and easy way to determine the optimum power output, based on a given enthalpy of a geothermal fluid. Five energy conversion systems were considered: double flash, single and second flash, organic Rankine cycle (ORC), advanced ORC and a Kalina cycle. These were assumed to be installed as a bottoming unit of a single flash plant. The optimum specific power output of the combined single flash and the bottoming units was determined, based on an enthalpy range of the geothermal fluid from 500 to 2,000 kJ/kg. Furthermore, a comparison of the optimum specific power outputs of the combined plants was performed. The study was based on the fundamental thermodynamic principles of energy and mass conservation, where a new methodology for modeling and optimization was used. Modeling was performed by using material data from the REFPROP7 database along with a Fortran to MATLAB interface. Optimization was performed by using robust state of the art techniques, based on evolutionary search. A cost analysis was also performed to obtain the specific leveled annual costs of the combined plants.

1. INTRODUCTION

Once geothermal wells have been drilled and production tests have been performed, we want to know how much power output can be generated. Furthermore, we want to know what kind of energy conversion system can best produce the optimum power output, utilizing the energy of the well fluid as much as possible. Many technological energy conversion systems are well known for power generation such as a dry steam plant, single flash, double flash, ORC and an advanced ORC system. The question is which of them can generate an optimum power output based on a given enthalpy of geothermal fluid?

In the liquid dominated field, single flash technology is the most installed as the first step of development. In many fields, the single flash plant has a considerable amount of hot waste liquid from the separator. This hot waste liquid poses a potential problem not only for the environment but also for power plant operation. This hot waste liquid sometimes cannot be directly re-injected to the re-injection well due to its high temperature. The hot liquid may cause the re-injection well to build up until becomes pressurized. When this happens the injection rate of the liquid will decrease and terminate. In some places, the hot liquid is collected in ponds before being re-injected into the re-injection wells. The level of a pond should always be monitored to avoid spillage into the environment. When the pond and re-injection well could not handle this waste

liquid, then the operation of the power plant should be limited and, in the worst case, be shut down.

Instead of direct re-injected to re-injection wells, the hot liquid could be utilized for additional power output. To produce additional power output, this waste liquid could be utilized by using a double flash or binary unit. It often happens that a single flash unit is built and has operated for many years, then the operator decides to utilize the waste liquid. Which of the combinations of a plant will give the optimum power output? It is not simple to determine which combination will give optimum power output. A comprehensive calculation must be performed with software to find the answer. This requires a lot of time and resources.

The objective of this study was to provide a guide or reference which could quickly and easily be used to determine the optimum power output and choose the most efficient energy conversion technology. The study also sought to provide a reference of the total annual costs needed to generate such a specific power output from different energy conversion systems. The results of this study were designed for general geothermal fluid and the references are based on enthalpy.

To provide such a guide, five energy conversion models were analyzed and simulated. Due to its simplicity and reliability, the single flash plant was chosen as the main energy conversion system. Five energy conversions were considered as the bottoming unit of the single flash: double flash, second flash, ORC, advanced ORC and the Kalina cycle.

The study performed modeling and simulation in order to obtain the optimum power output of the four energy conversion systems and make comparisons between them. A software called MATLAB along with a data base called REFPROP were used for the modeling and simulation.

2. MODELING AND THEORITICAL BACKGROUND

To utilize the hot waste liquid from a single flash separator, five models of the energy conversion systems were considered: double flash, combined single and second flash, combined single flash and ORC, combined single flash and advanced ORC and combined single flash and a Kalina cycle.

2.1 Double Flash Plant

In order to generate more power, a double flash plant was considered as the first model of the energy conversion system. It was assumed that it was possible to modify the existing single flash plant into a double flash plant. The double flash plant is an improvement on the single flash plant design and can produce more power output for the same conditions. In the double flash plant, the steam from the single flash turbine exhaust goes to the low pressure turbine instead of directly to the condenser. Then, it is combined with the steam from the low pressure separator. Figure 1 shows a simplified schematic diagram of a double

flash plant. The double flash plant's main equipment consists of a high and low pressure separator, a high and low pressure turbine, a condenser, a cooling tower and circulation water pump and a NCG compressor.

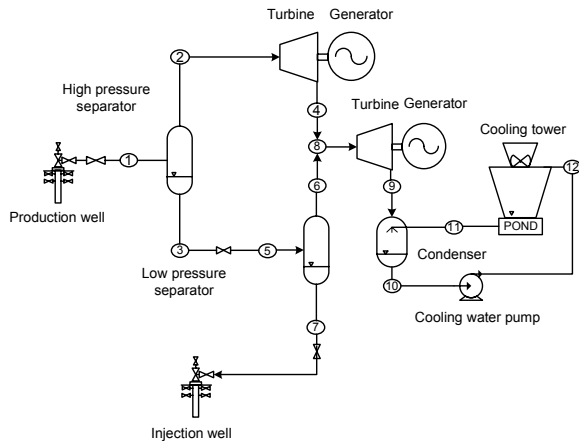


Figure 1: Simplified schematic diagram of a double flash plant.

Often a single flash unit has been operating for some time, and for some reason it is not possible to modify it into a double flash plant. To increase the power output of the existing single flash plant, a separate second flash plant is considered as the bottoming unit. The combined single and second flash is the second model to be simulated.

2.2 Combine Single and Second Flash

Figure 2 shows the simplified schematic diagram of a combined single and second flash plant. The combined plant consists of one single flash plant and one second flash plant. The second flash unit serves as a bottoming unit to utilize the waste hot liquid.

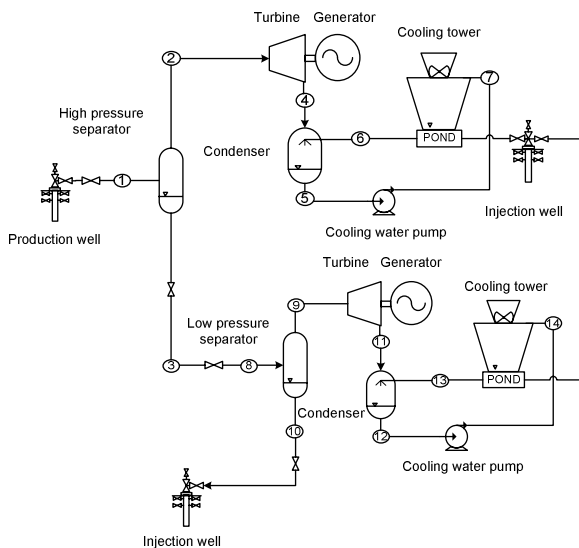


Figure 2: Simplified schematic diagram of a combined single and second flash plant.

The main components of a combined single and second flash plant are high and low pressure separators, high and low pressure turbines, condensers, a non condensable gas (NCG) compressor, cooling towers and a cooling water pump. To obtain the net power output, the turbine power and the auxiliary power of the plant should be calculated. The auxiliary power consists of all electric motor power which is

required to run the plant. In this model the electric motor of the cooling water pump, condensate pump, NCG compressor and fan cooling tower were to be auxiliary equipments.

For the third model, binary cycle technology was considered to utilize the hot waste liquid from a single flash separator.

2.3 Combine Single Flash and ORC Plant

Another possibility for generating more power from a single flash plant's hot waste liquid is by developing an ORC plant as the bottoming unit of the existing single flash plant. An ORC plant was added between the separator and the re-injection well. A simplified schematic diagram of a combined single flash and ORC plant is shown in Figure 3.

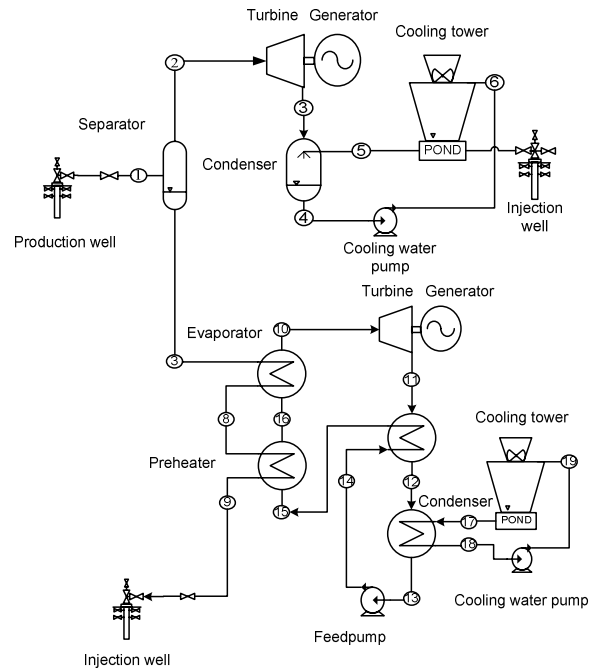


Figure 3: Simplified schematic diagram of a combined flash and ORC plant.

Similar to previous models, the single flash plant consists of separator, turbines, condenser, NCG compressor, cooling towers and cooling water pumps. To obtain the net specific power output, the turbine power and the auxiliary power of the plant were calculated. The auxiliary power consists of all electric motor power required to run the plant. In this model, the electric motor of the cooling water pump, the condensate pump, the NCG compressor and the fan cooling tower were considered auxiliary equipment.

An ORC plant consists of ten major components. They are: recuperator, pre-heater, evaporator, condenser, feed pump, turbine, generator, cooling tower and condensate pump. To obtain the specific power output, the turbine power and the auxiliary power of the plant were calculated. The auxiliary power consists of all electric motor power required to run the auxiliary equipment of the plant. In this model, the auxiliary equipment included a cooling water pump, a feed pump, NCG compressor and a cooling tower fan.

In the basic ORC, transferring heat across a large temperature difference between the hotter brine and the cooler working fluid causes losses in the process. To avoid the losses, a match of the brine cooling curve and working fluid heating curve should be closer. An advanced ORC was considered to reduce the heat losses which occurred in the

basic ORC. The advanced ORC was the next model considered in this study.

2.4 Combine Single Flash and Advanced ORC

The advanced ORC was modeled as a double pressure cycle. The heating process has two stages using two turbines with different pressures. A simplified schematic diagram of a combined single flash and advanced ORC plant is shown in Figure 4.

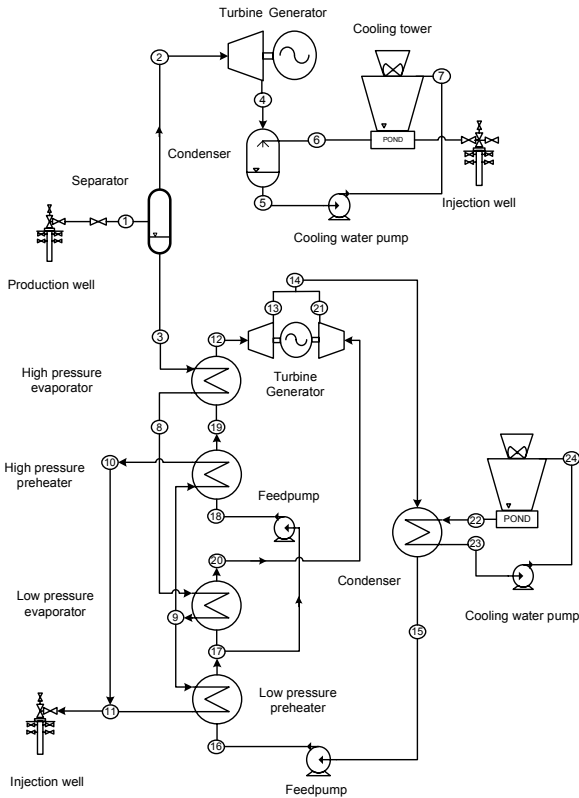


Figure 4: Simplified schematic of a combined single flash and advanced ORC plant.

The model of the advanced ORC plant's major components include two pre heaters, two evaporators, two turbines, two feed pumps, a condenser, a cooling tower and the cooling water pump. The other binary cycle model of the bottoming unit of the single flash system next considered is the Kalina cycle.

2.5 Combine Single Flash and Kalina Cycle Plant

The other advanced ORC is the Kalina cycle which uses a mixture of ammonia and water as the working fluid. The Kalina cycle may increase the efficiency of the basic ORC. In this study, a model of the Kalina cycle system 34 (KCS 34) was considered. This system was designed by Dr. Alex Kalina and implemented in Husavik, Iceland. A simplified schematic diagram of a combined single flash and Kalina plant is shown in Figure 5.

The main equipment of the plant includes a turbine, a generator, a separator, an evaporator, a recuperator, a condenser, a cooling tower, a cooling water pump, and a feed pump. The process of the ammonia and water mixture can be described starting from the condenser outlet where the mixture is in a saturated liquid phase. The mixture is pumped to a high pressure by the feed pump. The mixture is preheated in the low and high recuperator before entering the evaporator. In the evaporator, the working fluid is heated by the brine and the mixture partially is vaporized. Then the

mixture is separated by a separator into a vapor phase and a liquid phase. In the vapor phase, the ammonia fraction is high and in the liquid phase it is low. The saturated liquid mixture expands in the turbine and is cooled at low temperature and by low pressure exhaust. The saturated liquid phase from the separator is cooled in the high temperature recuperator where the sensible heat is used to preheat the mixture stream to the evaporator. The liquid saturated mixture is then sprayed into the vapor mixture from the exhaust turbine. They are mixed and reform the basic fluid mixture.

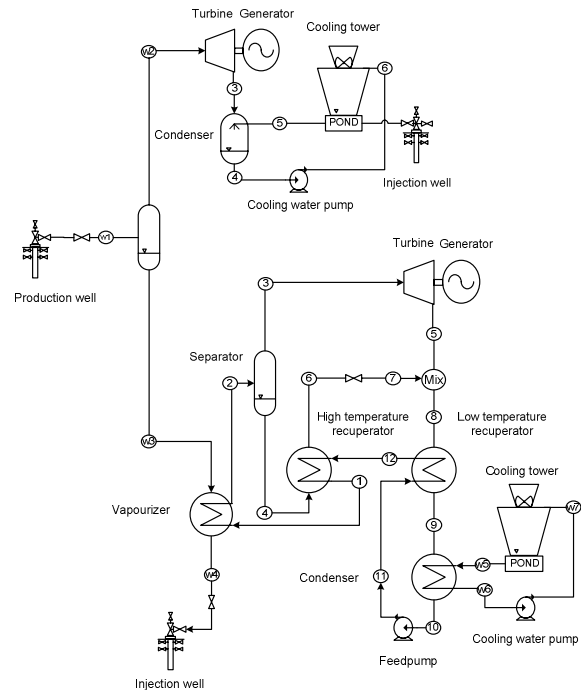


Figure 5: Simplified schematic diagram of a combined single flash and Kalina cycle plant.

2.6 The Main Auxiliary Equipment

The main auxiliary equipment is the main equipment required to support turbine and generator operations. The main auxiliary equipment in the energy conversion models included the cooling water pump, feed pump, NCG compressor and cooling tower. This equipment needs power to operate. The power used is called auxiliary power and must be taken into account to determine the net power output.

The cooling water pump is the pump which is used for cooling water circulated from the cooling tower pond to the condenser. The electric motor power of the cooling water pump was calculated to find the auxiliary power. The electric motor power was calculated based on different enthalpies between suction and discharge. It was assumed that the cooling water temperature in the cooling tower pond was 25°C and flowed to the condenser under pressure of 200 kPa. The efficiency of the pump was assumed to be 0.8.

The feed pump is used to circulate the working fluid of the ORC. It was calculated based on different enthalpies between suction and discharge. The efficiency of the pump was assumed to be 0.8.

The energy conversion models used a wet cooling tower with a mechanical draft. The wet cooling tower dissipates heat rejected by the plant to the environment by these mechanisms: 1) additional heat to the air and 2) evaporation

of a portion of the re-circulated water itself. In a mechanical draft cooling tower, the air is moved by one or more mechanically driven fans. Wet cooling tower calculation involves energy and mass balances. The energy balances here will be based on the first-law of the steady-state steady-flow (SSSF) equation. There are, however, three fluids entering and leaving the system: the cooling water, the dry air and the water vapor associated with it. The mass balance should also take into account these three fluids (El-Wakil, 1984).

2.7 Economic Models

The return of investment and the profit achieved are among the important indicators of the success of an engineering enterprise. Therefore, economic consideration plays a very important role in the decision making process that govern the design of a system. The costs incurred must be taken into account to make the effort economically viable.

This study presents an economic model to give an idea of the total cost needed to generate the optimum power output from five different combined plant models. The cost have been leveled annually for each combined plant models. The costs consists of the capital cost, operation and maintenance costs and the financial cost. Graphs of specific leveled annual costs versus enthalpy of geothermal fluid where then provided.

2.7.1 Capital Cost

The capital cost includes all expenses needed to put the power plant on line. These include the cost of the power plant and the gathering system, pipeline and pumps, pollution abatement systems and environmental compliance work, the electric sub-station and transmission line connection, civil work, engineering, legal, regulatory, documentation and reporting activities.

In this economic model, the capital cost for a double flash and combined single and second flash were assumed to be US\$ 1,295 and 1,236 per kW respectively. The capital cost of ORC, advanced ORC and Kalina cycle were assumed to be US\$ 2,259, 2,374 and 2,455 per kW respectively. These capital costs were higher than the flash system due to the complexity of the equipments.

2.7.2 Operation and Maintenance Costs

The objective of all projects is to be profitable, for geothermal project profits are related to the different between the price obtained for power and the cost of producing it. Operation and maintenance costs consist of all costs incurred during the operational phase of the power plant. Economic analysis usually distinguishes fixed and variable cost but in the case of geothermal power production, variable costs are relatively low. The marginal cost of the power production increase is, thus, considered to be minimal. Consequently, geothermal power plant operators have kept capacity as high as possible in order to minimize the cost of each kWh produced. This study simulated an economic model with an O&M cost of US\$ 0.015/kWh for flash plant and 0.02/kWh for binary plant.

2.7.3 Financial Factor

The financial structure, condition and related costs are an important factor influencing the leveled cost of energy and profitability of the project. Besides the amount of the initial capital investment, the origin of the money invested and the way it is secured will influence the resulting cost of power. The cost of borrowing money is directly related to the

interest rate and the length of debt period. These parameters may vary widely according to conditions and circumstances.

In this study, the capital structure of geothermal projects was assumed to be 30% equity and 70% loan. The cost of equity was assumed to be 15% and the cost of the loan was 6% per year. The loan was assumed to have a duration of about 15 years. The economic life time of the project was assumed to be 25 years. The salvage value of the project was assumed to be 30% of the initial value. The inflation rate was assumed to be 3% per year.

3. SIMULATION AND OPTIMIZATION

3.1 Model Simulation

Based on thermodynamic analysis, the specific power output of the models has been simulated. For simulation purposes, software named MATLAB was used. The name MATLAB stands for Matrix laboratory; it is a software package for high performance numerical computation and visualization. It provides an interactive environment with hundreds of built-in functions for technical computation, graphics and animation. it also provides easy extensibility with its own high-level programming language.

MATLAB also provides an external interface to run those programs with Fortran and C codes. MATLAB's built-in functions provide excellent tools for linear algebra computations, data analysis, optimization and many other scientific computations with state of the art algorithms. It is not limited to the built-in functions; a user's own functions can also be written in the MATLAB language (The Math Work, 2008).

Along with MATLAB, a data base called REFPROP was used. REFPROP is an acronym for reference fluid properties. This program, developed by the National Institute of Standards and Technology (NIST), provides tables and plots of the thermodynamic and transport properties of industrially important fluids and their mixtures with an emphasis on refrigerants and hydrocarbons, especially natural gas systems.

REFPROP is based on the most accurate pure fluid and mixture models currently available. It implements three models for the thermodynamic properties of pure fluids: equations of state explicit in Helmholtz energy, the modified Benedict-Webb-Rubin equation of state, and an extended corresponding state (ECS) model. Mixture calculations employ a model that applies mixing rules to the Helmholtz energy of the mixture components; it uses a departure function to account for the departure from ideal mixing. Viscosity and thermal conductivity are modeled with either fluid-specific correlations, an ECS method, or in some cases the friction theory method. These models are implemented in a suite of FORTRAN subroutines. They are written in a structured format, are internally documented with extensive comments, and have been tested on a variety of compilers. Routines are provided to calculate thermodynamic and transport properties at a given (T,x) state. Iterative routines provide saturation properties for a specified (T,x) or (P,x) state. Flash calculations describe single- or two-phase states given a wide variety of input combinations [(P,h,x), (P,T,x), etc] (Lemmon Eric, 2007).

3.2 Optimization

In power plant design, power output is one characteristic chosen for maximization. Workable designs are obtained over the allowable ranges of the design variable in order to satisfy the given requirements and constraints. This

optimization process requires specification of the function that is to be maximized. This function is known as the objective function and represents the aspect or feature that is of particular interest in a given circumstance.

The constraints in a given design problem arise due to limitations on the ranges of the physical variables and to basic conservation principles that must be satisfied. The restriction on the variables may arise due to the space, equipment, and material being employed. The optimization taken as the next step after obtaining a feasible design. The model and the simulation of the system are based on the conceptual design, which forms the starting point of the design.

With the exception of Kalina, it is sufficient to use a gradient based local optimization method. For this we use the function `fmincon` in the MATLAB optimization toolbox.

In the case of the Kalina model, some point in the search space cannot be computed. As a result the search space is no longer smooth and cannot be solved with `fmincon`, for this reason a global search method is needed. The global optimization method was also used to confirm the optimum results found by `fmincon`. The global optimization method used in this study is based on the work of Runarsson and Yao (Runarsson, 2000). This is an evolutionary optimization algorithm based on the evolution strategy (ES) (Schwefel, 1995).

3.2.1 Objective Function

This study considered five energy conversion conceptual designs as models including double flash, combined single and second flash, combined single flash and ORC, combined single flash and advance ORC and combined single flash and Kalina cycle. The models performed by the mathematical equations based on thermodynamic analysis. The objective function was power output per mass flow (kg/s) of geothermal fluid. To get the power output, auxiliary power such as the power consumption of an electric motor of a circulation water pump, NCG compressor and the cooling tower fan were taken into account.

3.2.2 Optimization Variables of a Double Flash Plant

To obtain the maximum specific power output of a double flash plant, three variables were chosen to be optimized. These variables were high and low separation pressures and the condenser pressure. For the optimization process, the variables were set with lower and upper boundaries, shown in Table 1 as enthalpy ranging from 500 to 2,000 kJ/kg. The optimization process found the optimum variable values which gave the maximum power output of the combined plant.

Table 1: Optimization variables of a double flash plant.

Variable (kPa)	Lower boundary	Upper boundary
High pressure separation	50	3000
Low pressure separation	50	500
Condenser pressure	8	10

3.2.3 Optimization Variables of a Combined Single and Second Flash Plant

To obtain the maximum specific power output of the combined single and second flash plant, four variables were optimized. These variables were: the high and low pressure separation processes, single flash condenser and second flash condenser. The four variables were set with lower and upper boundaries, shown in Table 2 as enthalpy ranging from 500 to 2,000 kJ/kg. The optimization process found the

optimum variable values which gave the maximum power output of the combined plant.

3.2.4 Optimization Variables of a Combined Single Flash and ORC Plant

To obtain the maximum specific power output of a combined single and ORC plant, four variables were chosen to be optimized. The variables were separation pressure, single flash's condenser pressure, ORC's condenser and turbine pressure.

Table 2: Optimization variables of a combined single and second flash plant.

Variable (kPa)	Lower boundary	Upper boundary
High pressure separation	50	2000
Low pressure separation	10	500
Single flash condenser	8	10
Second flash condenser	8	10

Table 3: Optimization variables of a combined single flash and ORC plant.

Variable (kPa)	Lower boundary	Upper boundary
Separation pressure	50	3000
SF Condenser pressure	8	10
Turbine pressure	100	1000
ORC's condenser pressure	100	200

The four variables were set with lower and upper boundaries, shown in Table 3 as enthalpy ranging from 500 to 2,000 kJ/kg. The optimization process found the optimum variable values which gave the maximum power output of the combined plant.

3.2.5 Optimization Variables of a Combined Single Flash and Advanced ORC Plant

To obtain the maximum specific power output of the combine single and advanced ORC plant, four variables were chosen to be optimized. The variables were separation pressure, single flash's condenser pressure, turbine high pressure and turbine low pressure of an advanced ORC plant. The four variables were set with lower and upper boundaries, shown in Table 4 as enthalpy ranging from 500 to 2,000 kJ/kg. The optimization process found the optimum variable values which gave the maximum power output of the total plant.

Table 4: Optimization variables of a combined single flash and advanced ORC plant.

Variable (kPa)	Lower boundary	Upper boundary
Separation pressure	100	3000
SF Condenser pressure	8	10
Turbine high pressure	100	3000
Turbine low pressure	100	1000

3.2.6 Optimization Variables of a Combined Single Flash and Kalina Cycle Model

The maximum specific power output of the combined single flash and Kalina cycle plant was obtained by optimizing four chosen variables. The variables were steam and water separation pressure, Kalina's turbine pressure, Kalina's turbine condenser and ammonia mass fraction. The four variables were set with lower and upper boundaries, shown in Table 5 as enthalpy ranging from 500 to 2,000 kJ/kg.

Table 5: Optimization variables of combined single flash and Kalina cycle plant.

Variable (kPa)	Lower boundary	Upper boundary
High pressure separation (kPa)	100	2000
Kalina turbine pressure (kPa)	1000	4000
Kalina condenser pressure (kPa)	600	1000
Ammonia mass fraction	0.5	0.9

3.2.7 Constraints

To avoid corrosion and deposition on turbine blades, the steam exhaust of the single and second flashes should be maintained in good condition. For the optimization process, the steam quality of the turbine exhaust was set as a constraint with a minimum quality of 0.85. Table 6 shows the constraint variables and the values for each combined plant.

Table 6: Constraint variables.

Combined plant	Single flash steam quality	Second flash steam quality
Double flash		0.85
Single&second flash	0.85	0.85
Single flash&ORC	0.85	
Single flash& advORC	0.85	
Single flash&Kalina	0.85	

4. RESULT AND DISCUSSION

4.1 The Optimum Specific Power Output of a Double Flash Plant

The optimum specific power output of the double flash plant for different enthalpies of geothermal fluid is shown in Figure 6. The red color line with triangular markers represents the specific power output of the high pressure turbine. The figure shows that the specific power output increases when enthalpy increases. Where enthalpy ranges from 500 to 2,000 kJ/kg, the optimum specific power output ranges from 5.8 to 319.3 kW/kg/s.

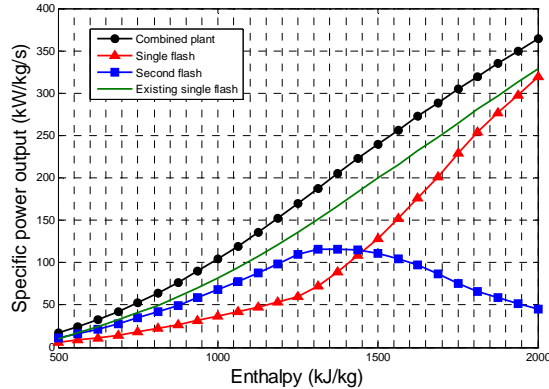


Figure 6: Specific power output of the double flash plant vs. enthalpy.

The blue color line with square markers represents the specific power output of a low pressure turbine. As the enthalpy increases from 500 to 1,375 kJ/kg, the specific power output of a low pressure turbine increases from 11.2 to 116.1 kJ/kg. Then, as the enthalpy increases from 1,375 to 2,000 kJ/kg, the specific power output decreases from 116.1 to 44.9 kW/kg/s. This is because the mass flow of fluid which comes to the low pressure turbine decreases as enthalpy increases.

The black color line with dot markers represents the performance of the total specific power output of the combined plant. As enthalpy increases from 500 to 2,000 kJ/kg, the specific power output of the combined plant increases from 17 to 364.3 kW/kg/s.

The optimum high pressure separation is defined as the pressure of the first separation process which gives the maximum output of the double flash plant.

Figure 7 shows the optimum high pressure separation for different enthalpies. The optimum separation pressure becomes higher when the enthalpy of the geothermal fluid increases from 500 to 1,750 kJ/kg. The optimum separation pressure becomes lower when enthalpy increases from 1,750 to 2,000 kJ/kg due to constraints on the steam quality of both exhaust turbines.

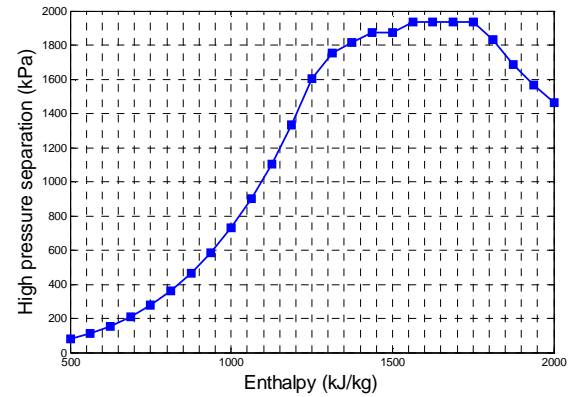


Figure 7: High pressure separation of the double flash plant vs. enthalpy.

The capital and O&M cost were levelized and calculated annually. For this model, the capital cost was assumed to be US\$ 1,294 per kW installed capacity and the O&M cost was US\$ 0.015 per kWh. Figure 8 shows the specific levelized annual cost of the combined plant at the optimum power output. As enthalpy increased from 500 to 2,000 kJ/kg, the specific levelized annual cost ranged from US\$ 1,138 to 24,360 per kg/s mass flow.

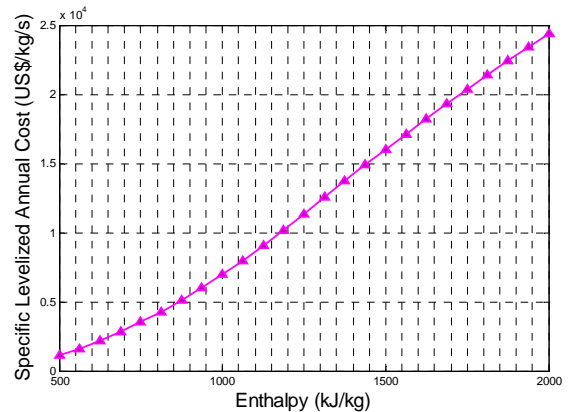


Figure 8: Specific levelized annual cost vs. enthalpy.

4.2 The Optimum Specific Power Output of a Combined Single and Second Flash Plant

The optimum specific power output of a combined single and second flash plant for different enthalpies of geothermal fluid is shown in Figure 9.

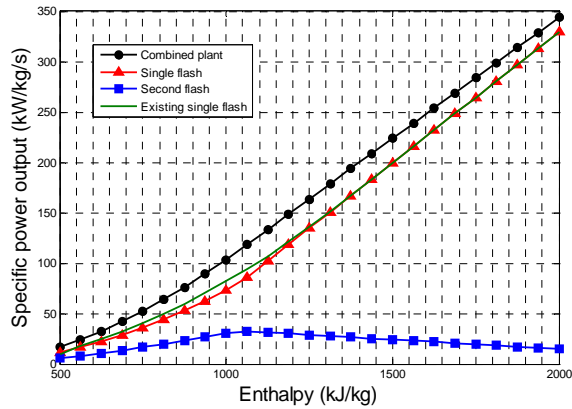


Figure 9: Specific power output of the combined single and second flash plant vs. enthalpy.

The red color line with triangular markers represents the specific power output of a single flash plant. The figure shows that the specific power output increases when the enthalpy becomes higher. As enthalpy increases from 500 to 2,000 kJ/kg the optimum specific power output ranges from 11.4 to 329.3 kW/kg/s.

The blue color line with square markers represents the specific power output of a second flash plant. As enthalpy increases from 500 to 1,063 kJ/kg, the specific power output of a second flash plant increases from 5.7 to 32.6 kJ/kg. When the enthalpy becomes higher than 1,063 kJ/kg, the specific power output of the second flash becomes lower. This is because with high enthalpy, the liquid mass fraction, which supposedly will be utilized by the second flash, is decreased.

The black color line with dot markers represents the performance of the combined plant. As enthalpy increased from 500 to 2,000 kJ/kg, the specific power output of the plant increased from 17.1 to 344 kW/kg/s.

The optimum high pressure separation for single flash is defined as the pressure of the first separation process which gives the maximum power output of the combined plant. Figure 10 shows the optimum high pressure separation for varied enthalpy. The optimum separation pressure becomes higher when the enthalpy of the well's fluid increases from 500 to 1,063 kJ/kg. Then, the optimum separation pressure remains constant at 849.1 kPa for any enthalpy higher than 1,063 kJ/kg.

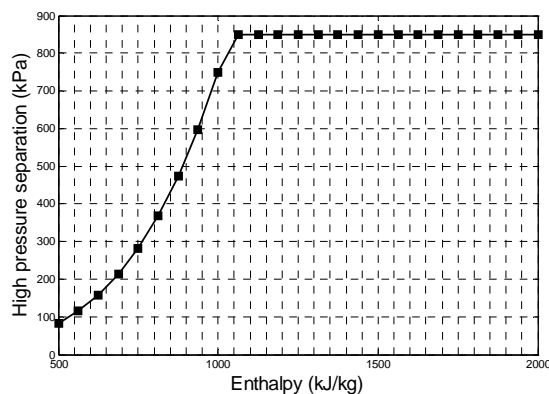


Figure 10: High pressure separation of a combined single and second flash plant vs. enthalpy.

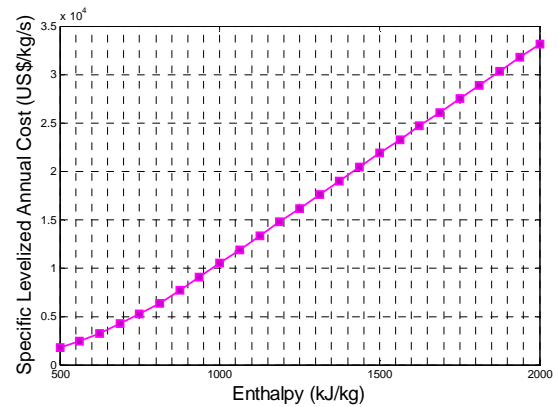


Figure 11: Specific leveled annual cost vs. enthalpy.

The capital, O&M cost were leveled and calculated annually. For this model the capital cost was assumed to be US\$ 1,236 per kW installed capacity and O&M cost was US\$ 0.015 per kWh. Figure 11 shows the specific leveled annual cost of the combined plant with the optimum power output as installed capacity. As enthalpy increased from 500 to 2,000 kJ/kg, the specific leveled annual cost increased from US\$1,158 to 23,240 per kg/s mass flow.

4.3 The Optimum Specific Power Output of a Combined Single Flash and ORC Plant

Figure 12 shows the optimum specific power output of the combined single flash and ORC plant for various enthalpies of the geothermal fluid. The red color line with triangular markers represents the specific power output of a single flash plant. The figure shows the specific power output increased when the enthalpy increased. As enthalpy increased from 500 to 2,000 kJ/kg, the optimum specific power output increased from 10.1 to 331.6 kW/kg/s.

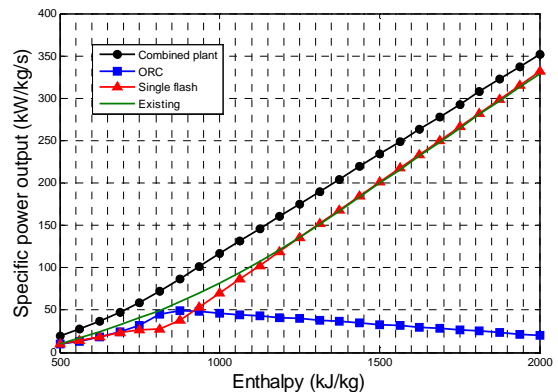


Figure 12: Specific power output of a combined single flash and ORC vs. enthalpy.

The blue color line with square markers represents the specific power output of the ORC plant. The ORC plant has been set as the bottoming unit. When enthalpy increased from 500 to 875 kJ/kg, the specific power output of the ORC plant increased from 9.4 to 49.5 kW/kg/s. When the enthalpy increased from 875 to 2,000 kJ/kg, specific power output decreased from 49.5 to 20.1 kW/kg/s as the high enthalpy of the liquid mass fraction which was supposedly utilized by the ORC plant decreased.

The black color line with dot markers represents the specific power output of the combined plant. As enthalpy increased from 500 to 2,000 kJ/kg, the specific power output of the combined plant increased from 19.5 to 351.7 kW/kg/s.

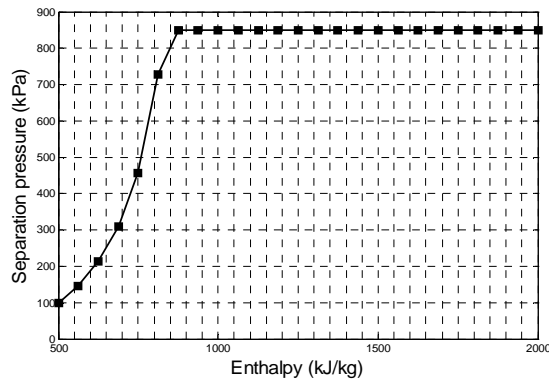


Figure 13: Separation pressure of a combined single flash and ORC vs. enthalpy.

The optimum separation pressure is defined as the vapor and liquid separation pressure which gives the maximum specific power output of the combined plant. Figure 13 shows the optimum separation pressure for differing enthalpy. The optimum separation pressure increased from 99.5 to 849.1 kPa as enthalpy of the geothermal fluid increased from 500 to 875 kJ/kg. The optimum separation pressure remained constant at 849.1 kPa in any enthalpy higher than 875 kJ/kg due to constraints on the steam quality of the single flash turbine exhaust.

Figure 14 shows the specific leveled annual cost of the combined plant with the optimum specific power output as the installed capacity. As enthalpy increased from 500 to 2,000 kJ/kg, the specific leveled annual cost increased from US\$ 1,737 to 33,160 per kg/s mass flow. The capital cost of single flash and ORC were assumed to be US\$ 1,236 and 2,259 per kW installed capacity. The O&M cost were assumed to be US\$ 0.015 and 0.017 per kWh respectively.

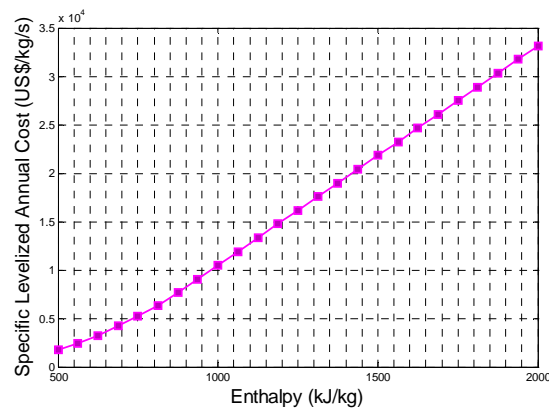


Figure 14: Specific leveled annual cost vs. enthalpy.

4.4 The Optimum Specific Power Output of a Combined Single Flash and Advanced ORC Plant.

Figure 15 shows the optimum specific power output of the plant for various enthalpies of the geothermal fluid. The red color line with triangular markers represents the specific power output of a single flash plant. The figure shows that the specific power output increased when enthalpy became higher. As the enthalpy increased from 500 to 2,000 kJ/kg, the optimum specific power output increased from 0 to 331.6 kW/kg/s.

The blue color line with square markers represents the advanced ORC plant. The specific power output increased from 20.6 to 71.6 kW/kg/s as enthalpy increased from 500 to

750 kJ/kg. As enthalpy increased from 750 to 2,000 kJ/kg the optimum specific power output decreased from 71.6 to 27.31 kW/kg/s.

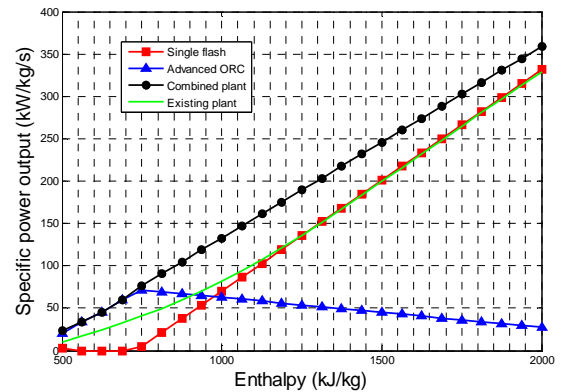


Figure 15: Specific power output of a combined single flash and advanced ORC vs. enthalpy.

The black color line with dot markers represents the total specific power output of the combined single flash and advance ORC plant. For an enthalpy range of 500 to 2,000 kJ/kg, the combined plant produced a specific power output range of 23.4 to 360.5 kW/kg/s. The advanced ORC produced the highest specific power output with an enthalpy of 750 kJ/kg. From that point, the specific power output of an advanced ORC decreased while the enthalpy of the well fluid increased. When the enthalpy of the fluid increased the liquid fraction that was supposed to be used for the advanced ORC decreased.

The optimum separation pressure is defined as the vapor and liquid separation pressure which gives the maximum specific power output of the combined plant. Figure 16 shows the optimum separation pressure for different enthalpies.

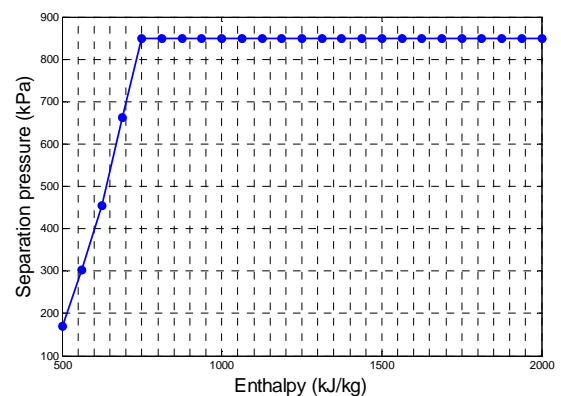


Figure 16: Separation pressure of combined single flash and advanced ORC vs. enthalpy.

The optimum separation pressure increased from 168.7 to 849.1 kPa as the enthalpy of the well fluid increased from 500 to 750 kJ/kg. The optimum separation pressure remained constant at 849.1 kPa for enthalpy higher than 750 kJ/kg due to constraints of the steam quality of single flash turbine exhaust.

Figure 17 shows the specific leveled annual cost of the combined plant with the optimum output power as the installed capacity. As enthalpy increased from 500 to 2,000 kJ/kg, the specific leveled annual cost ranged from US\$ 1,937 to 33,720 per kg/s fluid. The capital cost of a single

flash and advanced ORC plant were assumed to be US\$ 1,236 and 2,374 per kW installed capacity. The O&M cost were assumed to be US\$ 0.015 and 0.02 per kWh respectively.

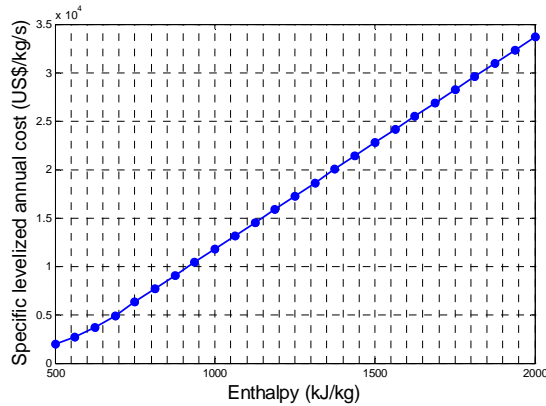


Figure 17: Specific leveled annual cost vs. enthalpy.

4.5 The Optimum Specific Power Output of a Combined Single Flash and Kalina Cycle Plant

The last model which was simulated and optimized is a combined single flash and Kalina cycle. This model dealt with a mixture of ammonia-water properties. The results shown in Figure 18 were definitely not good, even though this study attempt to find the reason why for future study.

Figure 18 suppose shows the optimum specific power output of the plant at various enthalpies of geothermal fluid. The red colored line with square markers represents the single flash plant's specific power output. The figure seems to be on the correct trend where the specific power output increased as the enthalpy increased from 500 to 2,000 kJ/kg. However, at one point, for an enthalpy of 1,818 kJ/kg, the result went lower than expected.

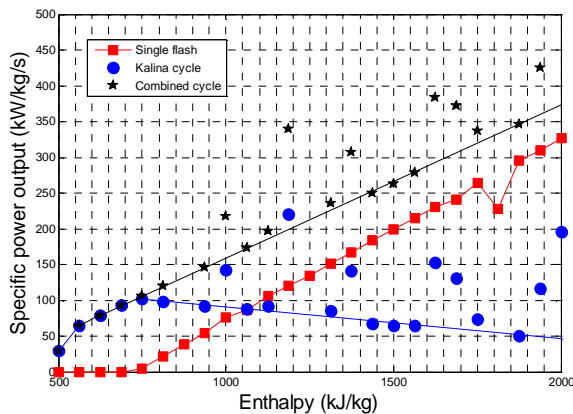


Figure 18: Specific power output of a combined single flash and Kalina cycle vs. enthalpy.

The blue color dot markers represents the specific power output of a Kalina cycle for a given enthalpy range of 500 to 2,000 kJ/kg. In the figure, it was difficult to recognize but if we made a line connecting the lower part of the results, we found the correct trend of the Kalina cycle specific power output. The incorrect results float above the blue line.

The black color star markers represents the total specific power output of the combined single flash and Kalina cycle plant. The results scattered but, again, if we made line on the lower part, we found that the trend was correct.

The correct trends of the single flash and Kalina cycle indicating that the model was not the problem and was working properly. The incorrect results were caused by the [Not a Number] of the mixture ammonia-water property data base. The data base, which was provided by REFPROP, was not sufficient to support simulation and optimization of a Kalina cycle. To obtain confident results on the Kalina cycle, the problem of the ammonia-water mixture's property data base should be addressed.

Due to an insufficient thermodynamic property data base, the MATLAB built-in optimization tool failed to run. A global search technique of the optimization tool was used to solve the optimization problem.

4.6 The Percentage of Additional Specific Power Outputs of the Combined Plants

The percentage of additional specific power outputs of the combined plants is shown in Figure 19. As the enthalpy ranged between 500 and 1,250 kJ/kg, the combined single flash and Advanced ORC plant gave the highest percentage of additional specific power output.

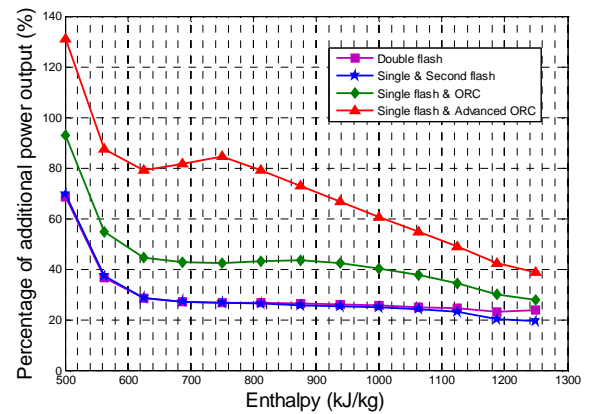


Figure 19: The percentage of additional specific power output of combined plants vs. enthalpy.

Figure 20 shows the percentage of specific power outputs of the combined plants vs. enthalpy ranging from 1,313 to 2,000 kJ/kg. For enthalpy ranging from 1,313 to 1,700 kJ/kg the combined single flash and advanced ORC plant produced the highest additional specific power output. For enthalpy ranging from 1,700 to 2,000 kJ/kg, the double flash plant gave the highest additional specific power output.

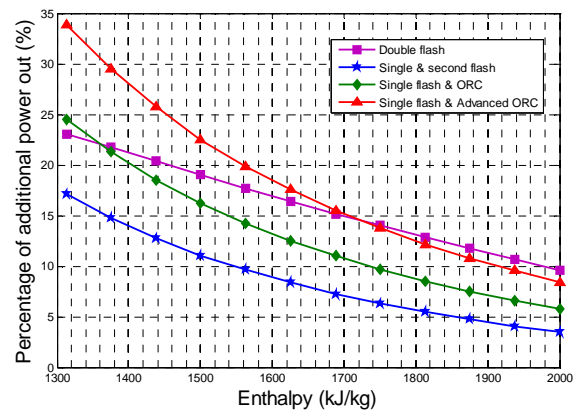


Figure 20: The percentage of additional specific power output of combined plants vs. enthalpy.

For enthalpy ranging from 500 to 2,000 kJ/kg, the percentage of specific power outputs of all the modeled plants is summarized in Table 7.

Table 7: The percentage of additional specific power outputs.

Combined plant	Percentage
Double flash	9.6 to 69
Single&second flash	3.5 to 70
Single flash&ORC	5.8 to 93
Single flash& advORC	8.4 to 131.2

A comparison of optimum high separation pressure of the combined plants is shown in Figure 21. The double flash plant has the highest range of optimum separation pressure from 80.8 to 1,937 kPa for enthalpy ranges from 500 to 2,000 kJ/kg.

4.7 A Fast and Easy Guide

The results of this study can be used as a fast and easy way to determine the optimum power output, based on a given enthalpy of geothermal fluid. Here is an example of how the guide works: A geothermal field has production wells with a total fluid enthalpy of 1,500 kJ/kg. The operator of the field plans to utilize the fluid of the wells for maximum power generation. He thinks about building a single flash plant as the initial plant and considers using a bottoming unit to utilize the waste hot liquid. The question is which kind of combined plant can produce the maximum power output and how much power can be generated?

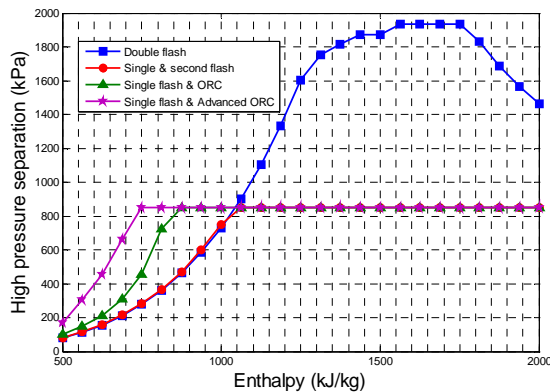


Figure 21: Comparison of separation pressures of different combined plants vs. enthalpy

The results of this study can be used to answer these questions quickly and easily. Figure 20 shows that with an enthalpy of 1,500 kJ/kg, the combined single flash and Advanced ORC cycle gives the highest additional specific power output to the existing plant, i.e. 22.5%. The specific power output of the combined plant for an enthalpy of 1,500 kJ/kg is 247 kW/kg/s, shown in Figure 15.

Figure 21 shows that for an enthalpy of 1,500 kJ/kg, the optimum separation pressure for combined plant is 849.1 kPa. From well's productivity curve, the specific mass flow rate at the separation pressure can be found. Let's say for separation pressure of 849.1 kPa the well supposed produces 100 kg/s of geothermal fluid. By multiplying 100 kg/s with 247 kW/kg/s, the combined single flash and Advanced ORC plant will produce 24.7 MW.

If the field operator, has decided to install a combined single and second flash plant due the simplicity and reliability, this

guidance can be used easily by using Figure 20. The blue color line gives the information needed: if the enthalpy of the fluid is 1,500 kJ/kg then the percentage of specific power output of a single and second flash plant is 11%. The specific power output of the combined plant for enthalpy of 1,500 kJ/kg is 223.7 kW/kg/s shown in Figure 9. The red line on Figure 21 gives the information that the optimum separation pressure for a combined single and second flash plant is 849.1 kPa. Then, if the mass flow rate at that separation pressure is 100 kg/s, the specific power output of the combined plant is 22.4 MW.

5. CONCLUSION

Five combined plants were simulated to generate the maximum specific power output of a given enthalpy. The double flash plant generated a specific power output of 17 to 364.3 kW/kg/s for enthalpy ranging from 500 to 2,000 kJ/kg. The specific leveled annual cost ranged from US\$1,138 to 24,360 per kg/s. The double flash plant gave a percentage of additional specific power output in a range from 9.6 to 69%. For enthalpy ranging from 1,700 to 2,000 kJ/kg, the double flash gave the highest additional specific power output.

The combined single and second flash plant generated a specific power output of 17.1 to 344 kW/kg/s for enthalpy ranging from 500 to 2,000 kJ/kg. The specific leveled annual cost ranged from US\$1,158 to 23,240 per kg/s. This combined plant had the lowest additional specific power output. For the enthalpy range from 500 to 2,000 kJ/kg, the combined single and second flash plant gave a percentage of additional specific power output in a range from 3.5 to 70%.

The combined single flash and ORC generated a specific power output from 19.5 to 351.7 kW/kg/s for enthalpy ranging between 500 and 2,000 kJ/kg. The specific leveled annual cost ranged from US\$1,737 to 33,160 per kg/s. For enthalpy ranging from 500 to 2,000 kJ/kg, the combined single flash and ORC gave a percentage of additional specific power output in a range from 5.8 to 93%.

The combined single flash and advanced ORC plant generated a specific power output of 23.4 to 360.5 kW/kg/s as enthalpy increased from 500 to 2,000 kJ/kg. The specific leveled annual cost to generate the optimum specific power output ranged from US\$ 1,937 to 33,720 per kg/s. For enthalpy ranging from 500 to 1,700 kJ/kg, the combined single flash and advanced ORC plant generated the highest percentage of additional specific power output in a range from 8.4 to 131.2%.

The combined single flash and Kalina cycle model did not have good results due to an insufficient thermodynamic data base for an ammonia-water mixture property in the simulation. Although a feasible result could not be obtained, the study provided an important discovery. For future research on Kalina cycle simulations the problem of the ammonia-water mixture property data base should be addressed.

The result of this study can be used as a fast and easy guide to determine the specific power output from five models of combined power plants. It can be used as a reference not only for new field which planned to install a combined plant where a single flash cycle plant as the main plant but also for the field which a single flash plant was currently installed. In the future, costs and optimum power outputs should be considered integrated objective functions to be optimized.

Optimization will find the best cost per kW per kg/s mass flow for a given enthalpy.

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