GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2009
Number 2

MODELLING AND OPTIMIZATION OF POSSIBLE BOTTOMING UNITS FOR GENERAL SINGLE FLASH GEOTHERMAL POWER PLANTS

MSc thesis
Department of Mechanical and Industrial Engineering
University of Iceland

by

Roy Bandoro Swandaru
PT. Pertamina Geothermal Energy
Menara Cakrawala (Skyline Building), 15th floor
Jl. MH. Thamrin No. 9, Jakarta 10340
INDONESIA

United Nations University
Geothermal Training Programme
Reykjavík, Iceland
Published in December 2009

ISBN 978-9979-68-267-7
ISSN 1670-7427

This MSc thesis has also been published in May 2009 by the
Faculty of Engineering – Department of Mechanical and Industrial Engineering
University of Iceland

INTRODUCTION

The Geothermal Training Programme of the United Nations University (UNU) has operated in Iceland since 1979 with six month annual courses for professionals from developing countries. The aim is to assist developing countries with significant geothermal potential to build up groups of specialists that cover most aspects of geothermal exploration and development. During 1979-2009, 424 scientists and engineers from 44 countries have completed the six month courses. They have come from Asia (43%), Africa (28%), Central America (15%), and Central and Eastern Europe (14%). There is a steady flow of requests from all over the world for the six month training and we can only meet a portion of the requests. Most of the trainees are awarded UNU Fellowships financed by the UNU and the Government of Iceland.

Candidates for the six month specialized training must have at least a BSc degree and a minimum of one year practical experience in geothermal work in their home countries prior to the training. Many of our trainees have already completed their MSc or PhD degrees when they come to Iceland, but several excellent students who have only BSc degrees have made requests to come again to Iceland for a higher academic degree. In 1999, it was decided to start admitting UNU Fellows to continue their studies and study for MSc degrees in geothermal science or engineering in co-operation with the University of Iceland. An agreement to this effect was signed with the University of Iceland. The six month studies at the UNU Geothermal Training Programme form a part of the graduate programme.

It is a pleasure to introduce the eighteenth UNU Fellow to complete the MSc studies at the University of Iceland under the co-operation agreement. Mr. Roy Bandoro Swandaru, BEng in Industrial Engineering, from PT. Pertamina Geothermal Energy, completed the six month specialized training in Geothermal Utilization at the UNU Geothermal Training Programme in October 2006. His research report was entitled "Thermodynamic analysis of preliminary design of power plant unit I Pathua, W-Java, Indonesia". After a year of geothermal research work in Indonesia, he came back to Iceland for MSc studies at the Faculty of Engineering – Department of Mechanical and Industrial Engineering of the University of Iceland in September 2007. In May 2009, he defended his MSc thesis presented here, entitled "Modelling and optimization of possible bottoming units for general single flash geothermal power plants". His studies in Iceland were financed by a fellowship from the Government of Iceland through the UNU Geothermal Training Programme. We congratulate him on his achievements and wish him all the best for the future. We thank the Faculty of Engineering of the University of Iceland for the co-operation, and his supervisors for the dedication.

Finally, I would like to mention that Roy´s MSc thesis with the figures in colour is available for downloading on our website at page *www.unugtp.is/publications.*

With warmest wishes from Iceland,

Ingvar B. Fridleifsson, director
United Nations University
Geothermal Training Programme

ACKNOWLEDGEMENT

I would like to express my gratitude to the United Nations University Geothermal Training Programme (UNU-GTP) for funding my master´s studies at the University of Iceland. I am very grateful to Dr. Ingvar B. Fridleifsson, the director of UNU-GTP and Mr. Lúdvík S Georgsson, deputy director of UNU-GTP and their staff for their support throughout my studies.

I sincerely thank my employer, PT Pertamina Geothermal Energy for assigning me to pursue this study and to the board of directors for their support throughout my study.

I wish to thank Dr. Halldór Pálsson and Professor Tómas Philip Rúnarsson for their best efforts in supervision and advice in making this project successful. I extend my thanks to Professor Páll Valdimarsson for critiques and advice.

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 2000 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 modelling and optimization was used. Modelling 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 levelized annual costs of the combined plants.

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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 it 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 cannot 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, and 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.

1.1 Motivation and literature

The single flash steam plant is the mainstay of the geothermal power industry. It is often the first power plant installed at a newly-developed liquid-dominated geothermal field. As of July 2004, there were 135 units of this kind in operation in 18 countries around the world. At that time, they constituted nearly 40% percent of the total installed geothermal power capacity in the world (Dipippo, 2005).

The double flash steam plant is an improvement on the single flash design in that it can produce 15 to 25% more power output for the same geothermal fluid conditions. The plant is more complex, more costly and requires more maintenance, but the extra power output often justifies the installation of such plants (Dipippo, 2005).

A previous study was performed to optimize the double flash power plant. The hypothetical double flash plant was assumed to be constructed in western Turkey conditions. The geothermal fluid had a temperature of 210 °C and mass flow rate of 200 kg/s. For these conditions, the optimum first and second flashing pressures were determined to be 530 kPa and 95 kPa, respectively (Dagdas, 2007).

Binary plants were the most widely used type of geothermal power plant with 155 units in operation as of July 2004. They constituted 33% of all geothermal units in operation but generated only 3% of the total power. Several binary units recently have been added to existing flash-steam plants to recover more power from hot, waste brine (Dipippo, 2005).

A dual pressure ORC cycle was designed to reduce the thermodynamic losses incurred in the brine heat exchangers of the basic cycle. The dual-pressure cycle has a two stage boiling process that allows the two fluids to achieve a smaller average temperature difference than in the one-stage process used in a basic cycle. The 5 MW Raft River Dual-boiling plant in Idaho, U.S. was the first to make use of the dual pressure concept (Dipippo, 2005).

A 5 MW pilot geothermal power plant was built by the Idaho National Engineering Laboratory at Raft River, Idaho, as an integral part of the Department of Energy's plan for commercial development of geothermal energy. The purpose of the plant was to investigate the technical feasibility of utilizing a moderate temperature hydrothermal resource (275-300°F) to generate electrical power in an environmentally acceptable manner. A variety of working fluids and cycles were initially studied for this moderate temperature resource application. It was found that the dual boiling cycle had a significantly better performance than either the single boiling cycle or the supercritical cycle when isobutane was the working fluid and the resource temperature was below 300°F (Bliem et al., 1983).

A new type of power system utilizing a variable composition, multi-component working fluid power cycle (conventionally referred to as a Kalina cycle) has been developed by Kalex LLC. This system is designed mainly for utilizing heat from liquid-dominated geothermal sources. The composition of the system's working fluid changes in different parts of the system, which allows the system to achieve high thermodynamical efficiencies (Kalina, 2003).

The Kalina cycle is principally a "modified" Rankine cycle. The transformation starts with an important process change to the Rankine cycle, changing the working fluid in the cycle from a pure component (typically water) to a "mixture" of ammonia and water. Compared to the conventional century-old Rankine cycle, a Kalina cycle power plant may offer efficiency gains of up to 50% for low heat energy sources such as geothermal brine at 150-210°C. Gains of up to 20% may be realized for higher temperature heat sources such as direct fired boilers and exhaust gases from a gas turbine, i.e. the bottoming cycle of a combined cycle plant (Mlcak, 1996).

A previous study about optimization of the maximum net power output was done with an interaction between the thermodynamic calculations in the software Engineering Equation Solver (EES) and an optimization routine in MATLAB by using the function fmincon. This was done because of restrictive problems of the optimization problem in the optimization routine provided in EES (Karlsdóttir, 2008).

Interest rates consist of the average cost of borrowing money using the London inter bank offering rate (LIBOR) to which the lender adds a compensation for the risk associated with its use. Most geothermal projects are financed with two different kinds of capital, 30% by equity and 70% by debt, characterized by different interest rates (Geothermal Energy Association, 2004).

The average capital cost of a binary cycle taken from 6 references was US$ 2,259 per kW installed capacity. The average capital cost of single flash technology taken from 8 references was US$ 1,236 per kW installed capacity. The average capital cost of double flash technology taken from 3 references was US$ 1,294 per kW installed capacity (Geothermal Energy Association, 2004). The capital cost of a 2 MW Kalina cycle power plant in Husavik, Iceland was Euro 3.7 M (Valdimarsson, 2003). The capital cost was about 2,455 US$/kW.

O&M cost of power plants are fairly variable and depend on the size of the power plant as well as various resource and site specific characteristics. In 2004, Sanyal estimated the O&M cost of a power plant ranging from 0.014-0.02 US$/kWh. These values do not include well make up drilling costs (Geothermal Energy Association, 2004).

A lot of hot waste liquid from single flash plants around the world is thrown away to the re-injection wells. Huge amounts of heat were not being utilized; however this potential energy could produce additional power output. It is really motivating to find a solution to gain additional power output instead of throwing it away to the re-injection well. Based on the literature, there is a possibility for generating power output from this hot waste liquid. Many of the energy converting systems have been studied and prove that they can generate additional power. A lot of researchers have been working to maximize the power output from some kind of energy converting system, and to find the best solution for utilizing the hot waste liquid, even though we do not, as yet, have a comprehensive solution. This study seeks to find a better solution for utilizing the hot waste liquid by using five models which represented available recent energy converting systems. It is also important to have some idea of the costs of the converted energy.

1.2 Objective and contribution

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 modelling 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 modelling and simulation.

The main contributions of this thesis are:

- A guide on how much specific power output can be generated by using five different energy conversion systems for a given enthalpy.

- An illustration of how REFPROP can be applied for the simulation of five different energy conversion models and the pitfalls in using REFPROP.

- How a global evolutionary search technique is necessary when REFPROP is unable to return feasible solutions.

1.3 Overview

This thesis is organized as follows. In Chapter 2, modelling and the theoretical background for the five models of the energy conversion systems are presented. Economic considerations are also given. In Chapter 3, the simulation program using MATLAB along with REFPROP is presented as are the optimization methods proposed to maximize the specific power output of the plants. In Chapter 4, the results of the optimization are discussed and optimal designs are presented. The thesis concludes with a discussion of the main findings and contributions along with proposed future research.

2. MODELLING AND THEORETICAL BACKGROUND

To utilize the hot waste liquid from a single flash separator, five models of 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.

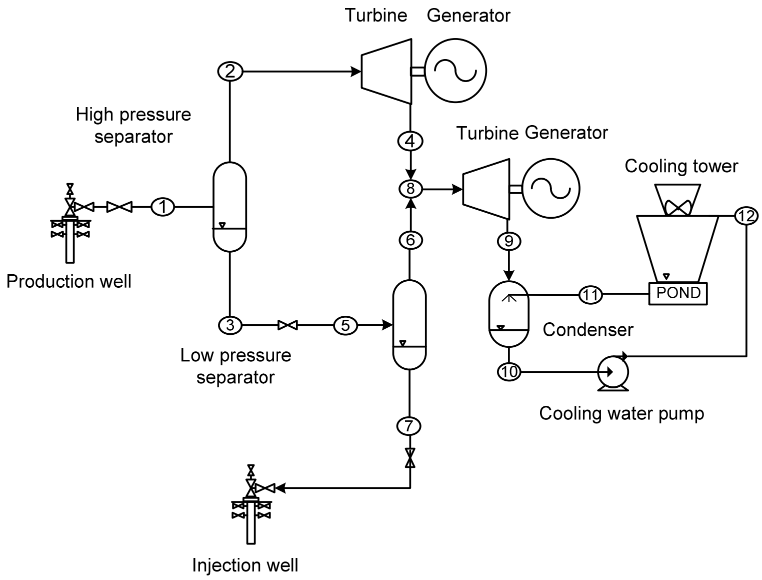

FIGURE 1: Simplified schematic diagram of a double flash plant

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.

The temperature vs. entropy state diagram of the double flash plant is shown in Figure 2. It describes the thermodynamic process of the geothermal fluid. State 1 is the process of the compressed fluid which came from the well and flashes toward the separator inlet. The process is modelled as one at isenthalpy, adiabatic and without work involvement. Also, the kinetic or potential energy of the fluid is constant. State 1 to State 2 and 3 is the separation process of the geothermal fluid into saturated vapour and a saturated liquid phase. The process takes place in the high pressure separator and is modelled as isobaric.

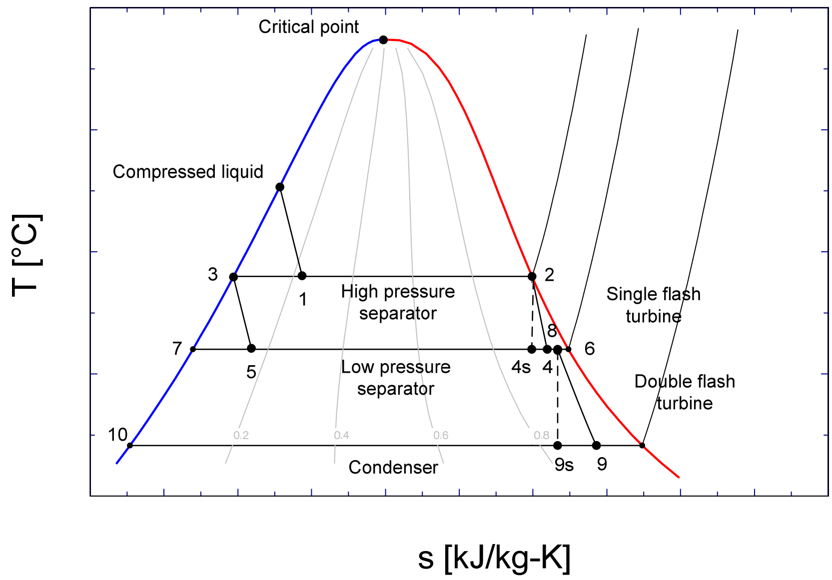

FIGURE 2: T-s state diagram for a double flash plant

In State 3, the saturated liquid goes to the inlet of the low pressure separator. The fluid flashes for the second time and is separated into a vapour phase at State 6 and a liquid phase at State 7. Similarly as in the high pressure separator, the process is isobaric. State 2 to 4s is the ideal process of the fluid in the high pressure turbine. It is an isentropic process and State 4 shows the entropic turbine efficiency. State 8 shows the mixing process of the fluid from the high pressure turbine exhaust and steam from the second separator. State 8 to 9s is the ideal process of the well fluid in the low pressure turbine. It is an isentropic process and State 9 shows the isentropic turbine efficiency. State 10 shows the process of the fluid at the outlet of the condenser of the double flash pressure.

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 Combined single and second flash

Figure 3 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.

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 condensible 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 electrical motor power which is required to run the plant. In this model the electric motors of the cooling water pump, condensate pump, NCG compressor and fan cooling tower were auxiliary equipment.

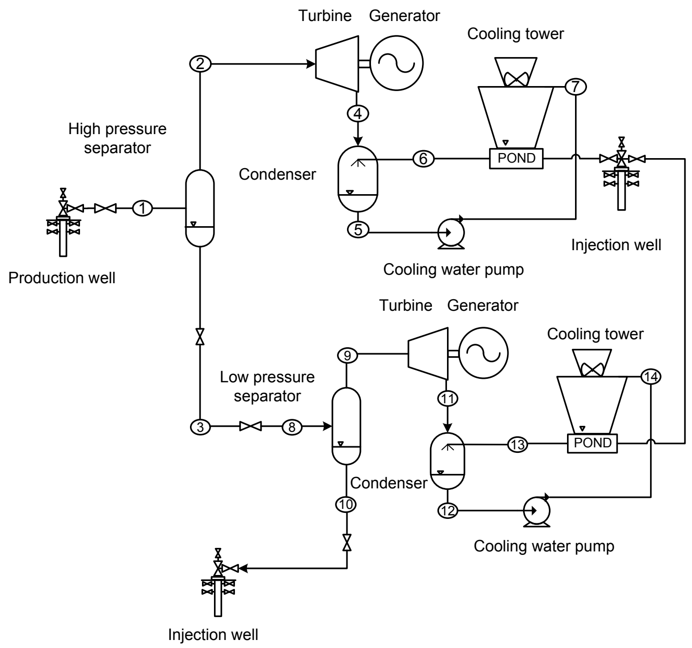

FIGURE 3: Simplified schematic diagram of a combined single and second flash plant

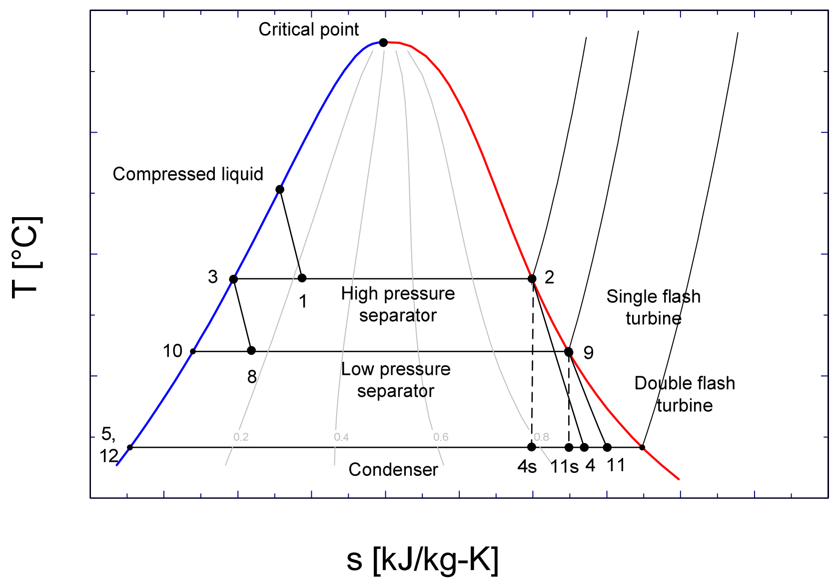

FIGURE 4: T-s state diagram for a combined single and second flash plant

Figure 4 shows the temperature vs. entropy state diagram of a combined single and second flash plant. It describes the thermodynamic process of the geothermal fluid. State 1 is the process of the compressed fluid which came from the well, and flashed toward the inlet of the separator. The process is modelled as one at isenthalpy, adiabatic and without work involvement. Also, the kinetic or potential energy of the fluid is constant. State 1 to State 2 and 3 is the separation process of the geothermal fluid into the vapour phase and liquid phase. The process takes place in the high pressure separator and is modelled as isobaric. From State 3, the saturated liquid goes to the inlet of the low pressure separator. The saturated liquid is flashed and separated into a vapour phase at State 9 and a liquid phase at State 10. Similar to the high pressure separator, the process is isobaric.

State 2 to 4s is the ideal process of the geothermal fluid in the single flash turbine. It is an isentropic process and State 4 shows the isentropic turbine efficiency. State 5 shows the process of the fluid at the outlet of the condenser of the single flash pressure. State 9 to 11s is the ideal process of the geothermal fluid in the second flash turbine. It is an isentropic process and State 11 shows the isentropic turbine efficiency. State 12 shows the process of the fluid at the outlet of the condenser of the second flash pressure.

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

2.3 Combined 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 5.

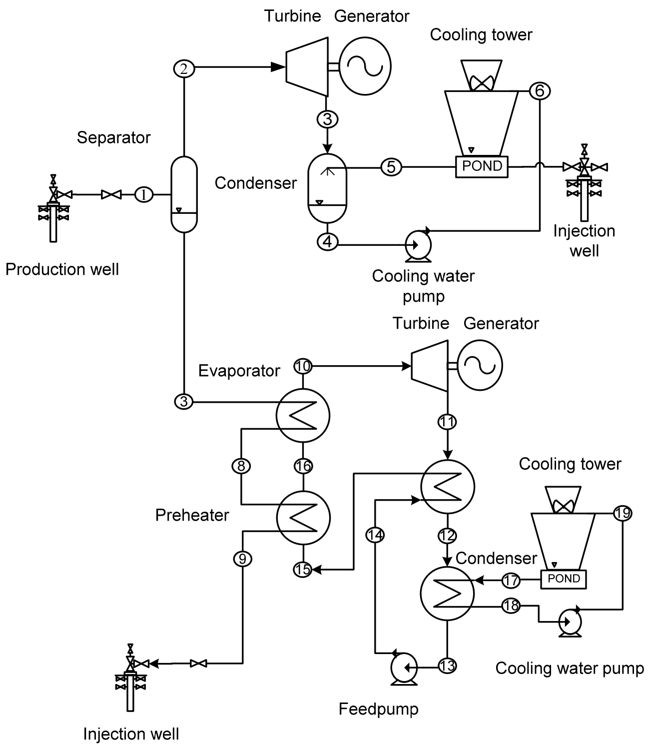

FIGURE 5: Simplified schematic diagram of a combined single and ORC plant

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 electrical motor power required to run the plant. In this model, the electric motors 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, preheater, 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 electrical motor power required to run the auxiliary equipment of the plant. In

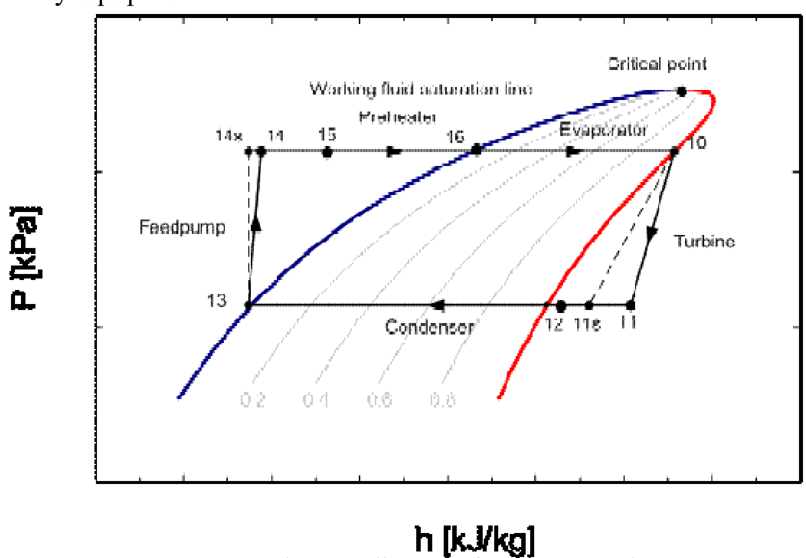

FIGURE 6: P-h state diagram for an ORC plant

this model, the auxiliary equipment included a cooling water pump, a feed pump, NCG compressor and a cooling tower fan.

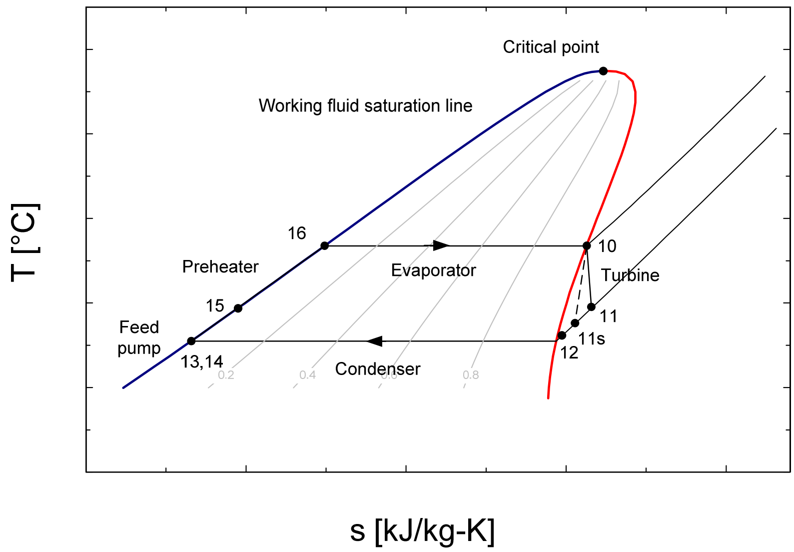

FIGURE 7: T-s state diagram for an ORC plant

The ORC plant was assumed to use isopentane as the working fluid. Figure 6 shows a pressure vs. enthalpy diagram of the isopentane, and the temperature vs. entropy is shown in Figure 7. States 13 to 14s show the ideal process of the isopentane in the feed pump. It is isentropic and an isenthalpic process. The isentropic efficiency of the actual work is shown by State 14. In State 14, the isopentane is under inlet turbine pressure.

After being heated by a reheater and preheater the isopentane comes to State 16, the saturated liquid phase. In State 10, the isopentane heated into saturated vapour. From State 10 to 11s the isopentane is expanded in the turbine in an isentropic process. It is an ideal process, but in the actual process, it is corrected by the isentropic efficiency so the isopentane comes to State 11. State 13 is the saturated liquid phase following the condensation process; it is isobaric and isothermal.

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 Combined single flash and advanced ORC

The advanced ORC was modelled 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 8. The model of the advanced ORC plant's major components include two preheaters, two evaporators, two turbines, two feed pumps, a condenser, a cooling tower and the cooling water pump.

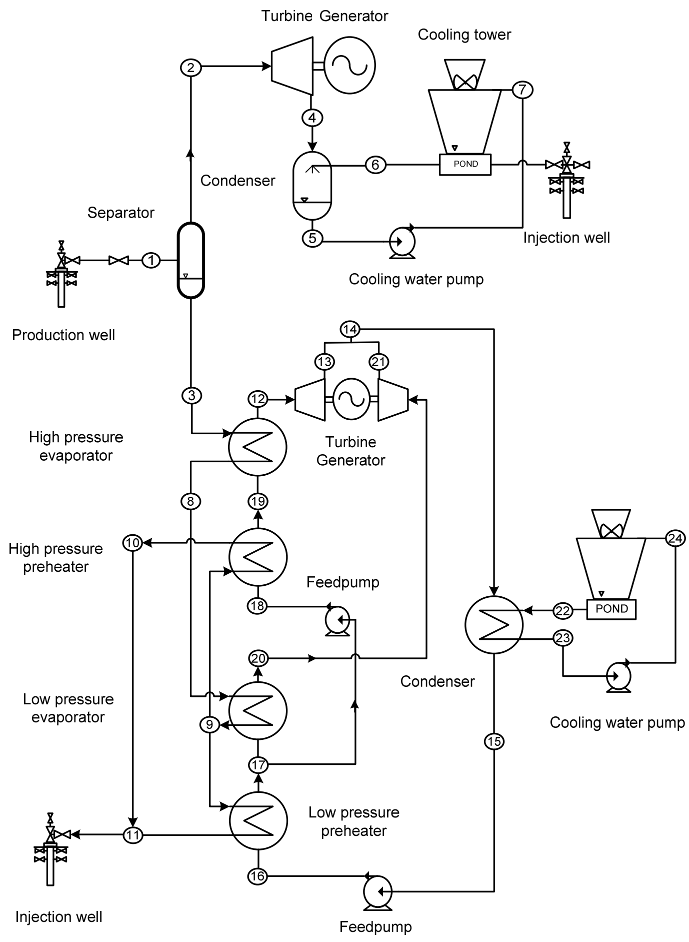

FIGURE 8: Simplified schematic of a combined single flash and advanced ORC plant

Figure 9 is the pressure vs. enthalpy state diagram of the isopentane as a working fluid, and the temperature vs. entropy state diagram is shown in Figure 10. The figure shows the process in the combined single flash and advanced ORC model. The model of the advanced ORC plant was assumed to use isopentane as the working fluid. State 15 to 16s shows the ideal process of isopentane in the low pressure feed pump; it is isentropic and an isenthalpic process. Due to isentropic efficiency, the actual work is shown by State 16. In State 16, the isopentane is under the inlet low pressure turbine. After being heated by a preheater the isopentane comes to State 17, the saturated liquid phase. In State 17, the mass flow isopentane is separated into two parts. The first part is pumped by the second feed pump to the high pressure preheater. The second part of the isopentane flows to the low pressure evaporator.

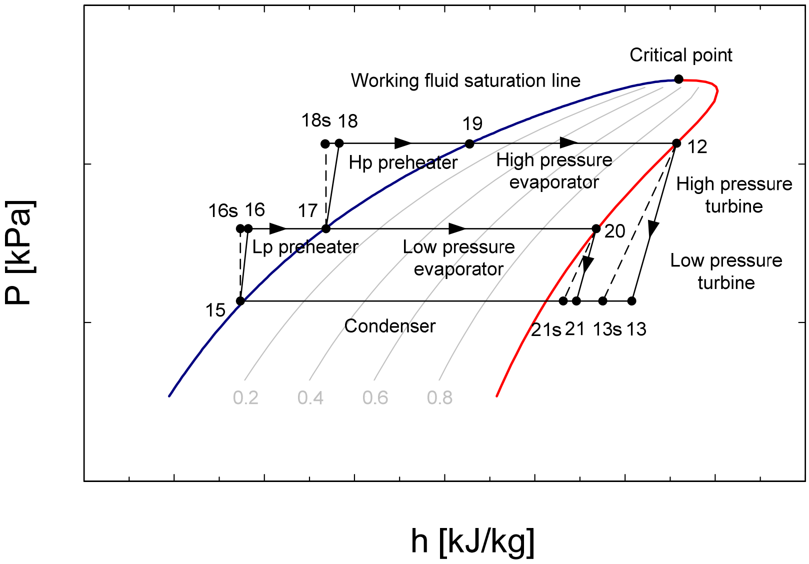

FIGURE 9: P-h state diagram for an advanced ORC plant

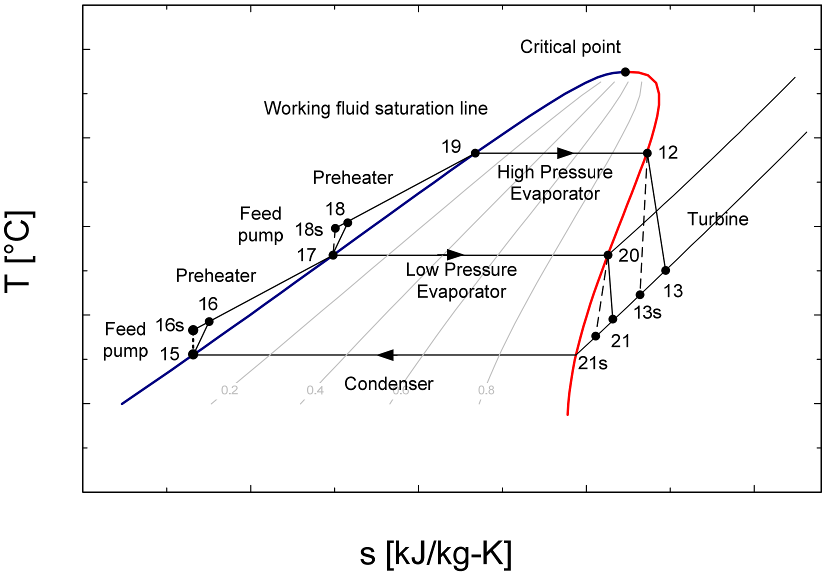

FIGURE 10: T-s state diagram for an advanced ORC plant

The first part of the isopentane mass, heated at the preheater, becomes the saturated liquid phase at State 19. In State 12, the isopentane is heated in the high pressure evaporator to a saturated vapour phase. From State 12 to 13s the isopentane is expanded in the high pressure turbine in the isentropic process. Its shows the ideal process but in actuality, the process is corrected by the isentropic efficiency so the isopentane comes to State 13. In State 20 the second part of the isopentane is heated to a saturated vapour phase. From State 20 to 21s, the isopentane is expanded in the low pressure turbine in the isentropic process. Its shows the ideal process but in actuality, the process is corrected by the isentropic efficiency so the isopentane moves into State 21. State 15 is the saturated liquid phase after the condensation process; it is isobaric and isothermal. The other binary cycle model of the bottoming unit of the single flash system next considered is the Kalina cycle.

2.5 Combined 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 11. The main equipment of the plant includes a turbine, a generator,

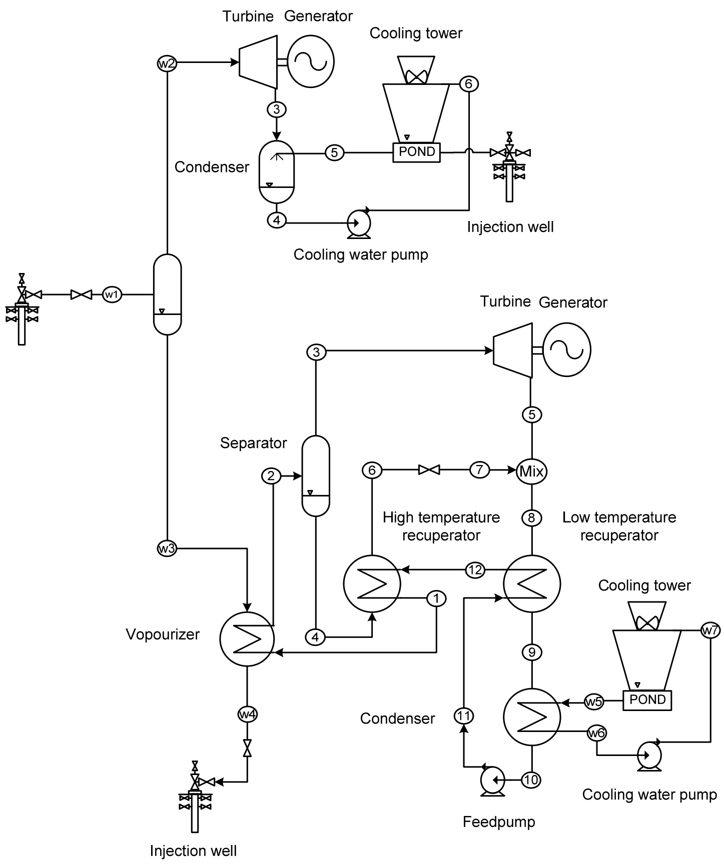

FIGURE 11: Simplified schematic diagram of a combined single flash and Kalina cycle plant

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 is partially vaporized. Then the mixture is separated by a separator into a vapour phase and a liquid phase. In the vapour 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 vapour mixture from the exhaust turbine. They are mixed and reform the basic fluid mixture.

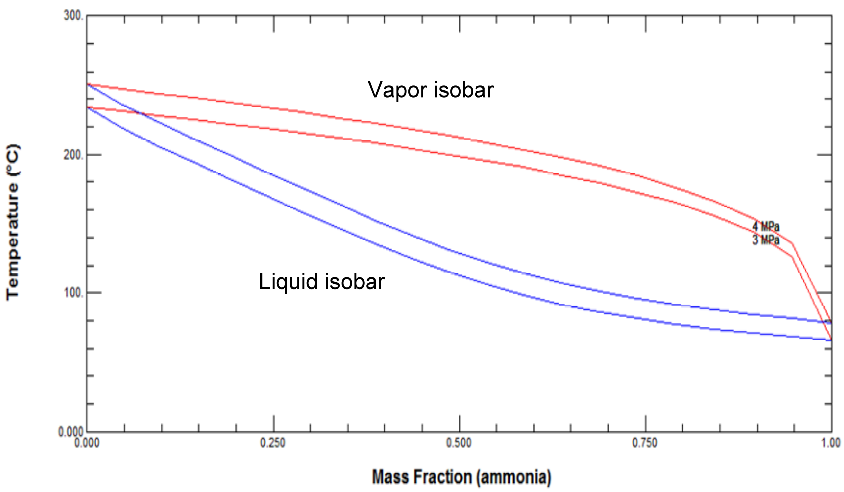

FIGURE 12: T-x diagram of ammonia-water

Figure 12 shows the temperature vs. ammonia mass fraction diagram. It is a mixture of 80/20 ammonia-water at a pressure of 3 and 4 MPa. States 1 and 2 are the saturation points of pure water, the point where the water boils and the steam condenses. States 3 and 4 are the saturation points of pure ammonia. The lower part of the curve is the saturated liquid or boiling point for the different ammonia and water mass fractions at a pressure of 3 and 4 MPa. The upper part of the curve is the saturated vapour of ammonia and water mass fraction.

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 electrical motor power of the cooling water pump was calculated to find the auxiliary power. The electrical 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 recirculated 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 vapour 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 governs 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 costs have been levelized annually for each combined plant model. The costs consist of the capital cost, operation and maintenance costs and the financial cost. Graphs of specific levelized annual costs versus enthalpy of geothermal fluid were 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 equipment.

2.7.2 Operation and maintenance costs

The objective of all projects is to be profitable, for geothermal project profits are related to the difference 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 per kWh for a flash plant and US$ 0.02 per kWh for a binary plant.

2.7.3 Financial factor

The financial structure, condition and related costs are an important factor influencing the levelized 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 lifetime 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.

2.7.4 Time value of the money

A concept that is of crucial importance in any economic analysis is that of the worth of money as a function of time. The value increases with time due to interest accumulation, making the same payment or loan at different times lead to different amounts at a common point in time. Similarly, inflation erodes the value of money by reducing its buying capacity as time elapses. Both value over time and inflation are important in calculating and estimating costs, returns, and other financial transactions.

In order to compare or combine amounts at different times, it is necessary to bring these all to a common point in time. Different costs, over the expected duration of a project, and the anticipated returns can then be considered to determine the rate of return on the investment and the economic viability of the enterprise. Two approaches that are commonly used for bringing all financial transactions to a common time frame are the present and future worth of an investment, expenditure, or payment.

Frequently, a loan is taken out to acquire a given facility and then this loan is paid off in fixed payments over the duration of the loan. Recurring expenses for maintenance and labour may be treated similarly as a series of payments as they are frequently the result of inflation which, in turn, gives rise to increased costs. The series of payments is also brought to a given point in time for consideration with other financial aspects.

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 MathWorks, 2008).

Along with MATLAB, a database 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 modelled 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, ñ, 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 et al., 2007).

3.2 Optimization

The need to optimize is very important in designing a power plant and has become particularly crucial in recent times due to growing global competition. It is no longer enough to obtain a workable system that performs the desired tasks and meets the given constraints. At the very least, several workable designs should be generated and the final design, which minimizes or maximizes an appropriately chosen quantity, selected from these. Many parameters affect the performance and cost of a power plant. Therefore, due to the varied parameters, an optimum can often be obtained in quantities such as power per unit, fuel input, cost, efficiency and other features of the plant.

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 is 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.

Mathematically we define the general nonlinear programming problem as follows:

Maximize $$P(\vec{x}), \vec{x} = (x_1, ..., x_n) \in \Re^n \quad (3.1)$$

where $P(\vec{x})$ is the objective function, specific power output, $\vec{x} \in S \cap F, S \subseteq \Re^n$ defines the *search space* which is an n-dimensional space bounded by the *parametric constraints* (upper and lower bounds). The decision variables x are pressures for the different models.

$$\underline{x}_j \leq x_j \leq \bar{x}_j, j \in \{1, ..., n\} \quad (3.2)$$

and the *feasible region F* is defined by

$$F = \{\vec{x} \in \Re^n \mid g_k(\vec{x}) \leq 0 \forall k \in \{1, ..., m\}\}, \quad (3.3)$$

where $g_k(\vec{x})$, $k \in \{1, ..., m\}$, are *inequality constraints* for the steam quality for all models investigated, 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 (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 were 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 2000 kJ/kg. The optimization process found the optimum

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

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

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 2000 kJ/kg. The optimization process found the optimum variable values which gave the maximum power output of the combined plant.

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

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. The four variables were set with lower and upper boundaries, shown in Table 3 as enthalpy ranging from 500 to 2000 kJ/kg. The optimization process found the optimum variable values which gave the maximum power output of the combined plant.

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

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 cycle 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 2000 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 cycle turbine pressure, Kalina cycle 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 2000 kJ/kg.

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

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

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	1000
Single flash & adv ORC	0.85	0.9
Single flash & Kalina	0.85	

4. RESULTS AND DISCUSSION

4.1 The optimum specific power output of a double flash plant

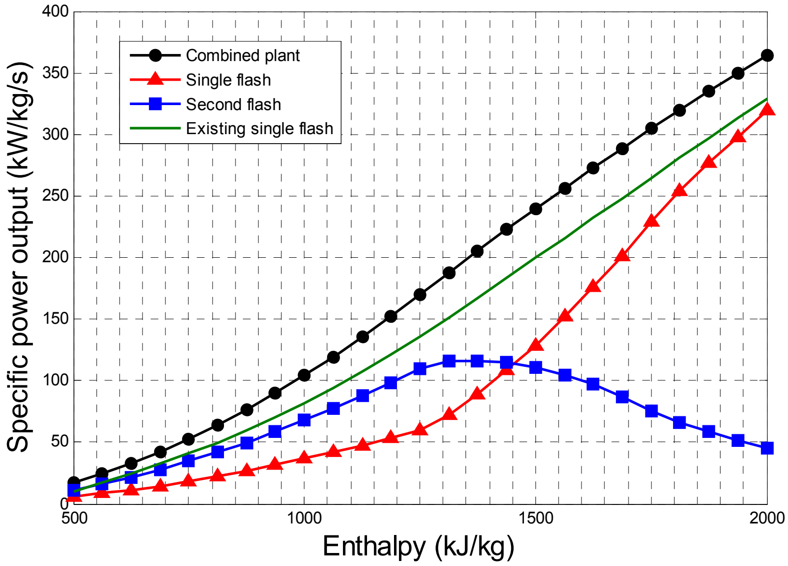

FIGURE 13: Specific power output of the double flash plant vs. enthalpy

The optimum specific power output of the double flash plant for different enthalpies of geothermal fluid is shown in Figure 13. The red colour 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 2000 kJ/kg, the optimum specific power output ranges from 5.8 to 319.3 kW/kg/s.

The blue colour line with square markers represents the specific power output of a low pressure turbine. As the enthalpy increases from 500 to 1375 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 2000 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 colour line with dot markers represents the performance of the total specific power output of the combined plant. As enthalpy increases from 500 to 2000 kJ/kg, the specific power output of the combined plant increases from 17 to 364.3 kW/kg/s.

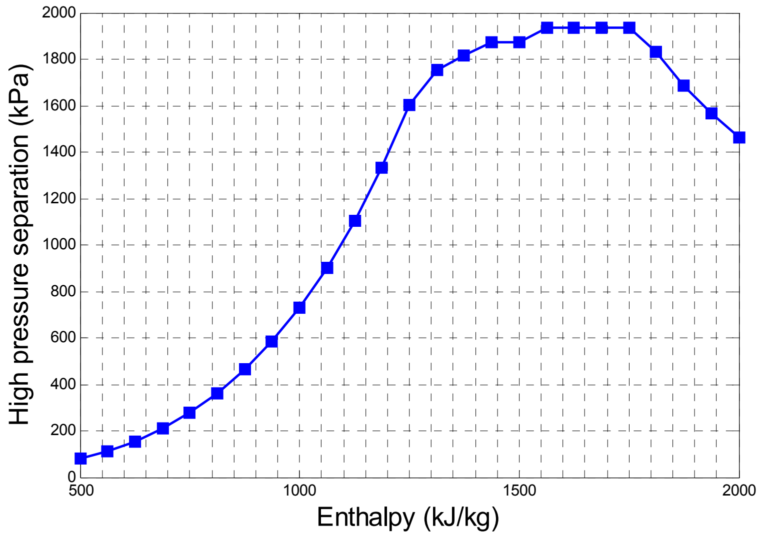

FIGURE 14: High pressure separation of the double flash plant vs. enthalpy

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 14 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 1750 kJ/kg. The optimum separation pressure becomes lower when enthalpy increases from 1750 to 2000 kJ/kg due to constraints on the steam quality of both exhaust turbines.

The optimum low pressure separation is defined as the pressure of the second separation process which gives the maximum output of the double flash plant. Figure 15 shows the optimum low pressure separation for different enthalpies. The optimum separation pressure increases from 30.4 to 195.2 kPa as enthalpy increases from 500 to 1250 kJ/kg. Then, the optimum low pressure separation decreases to 19.2 kPa as the enthalpy increases to 2000 kJ/kg, due to constraints on the steam quality of the second flash exhaust turbine.

The optimum low pressure turbine's condenser pressure is defined as the low pressure turbine's condenser pressure which gives the maximum power output of the double flash plant.

The results show that the optimum low pressure turbine's condenser pressure of the double flash plant remains constant at 8 kPa as enthalpy increases from 500 to 2000 kJ/kg, due to the lower boundary of the condenser pressure in the optimization process. The condenser pressure is not only related to the turbine power but also to the cooling tower capacity, fan power, cooling water and the condensate pumps.

To avoid turbine blade damage by low quality of steam, the steam of the turbine exhaust was set as a constraint with a minimum quality of 0.85. Figure 16 shows the steam quality of the high and low pressure turbine exhaust. The red line with dot markers represents the steam quality of the high pressure turbine exhaust. As enthalpy increases from 500 to 2000 kJ/kg, the steam quality of the high pressure turbine exhaust decreases from 0.96 to 0.85.

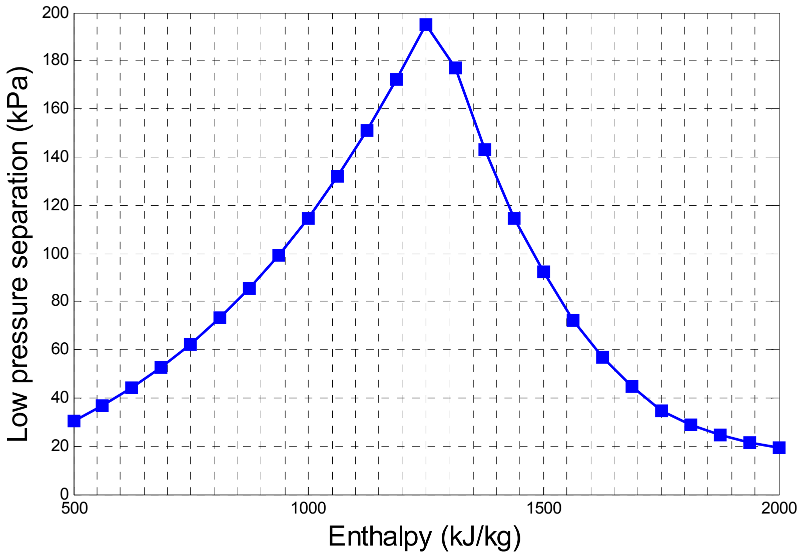

FIGURE 15: Low pressure separation of the double flash plant vs. enthalpy

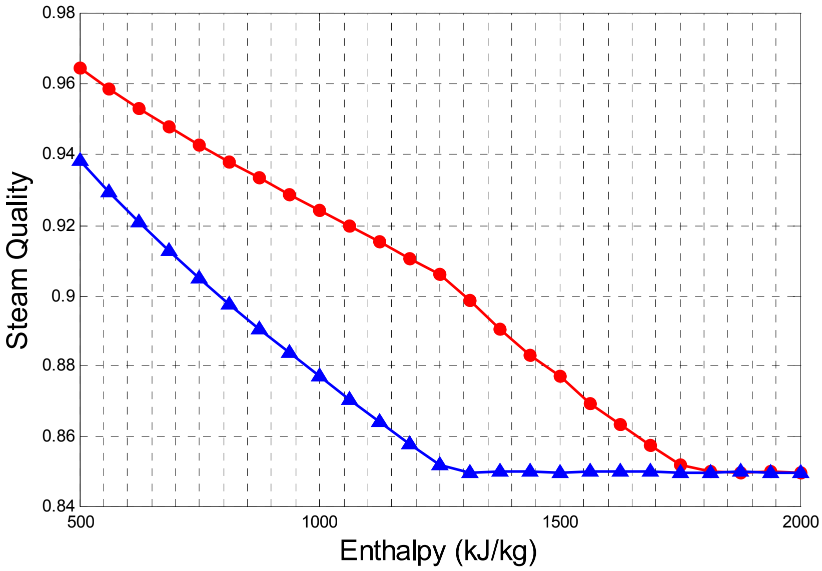

FIGURE 16: Double flash turbine exhaust steam quality vs. enthalpy

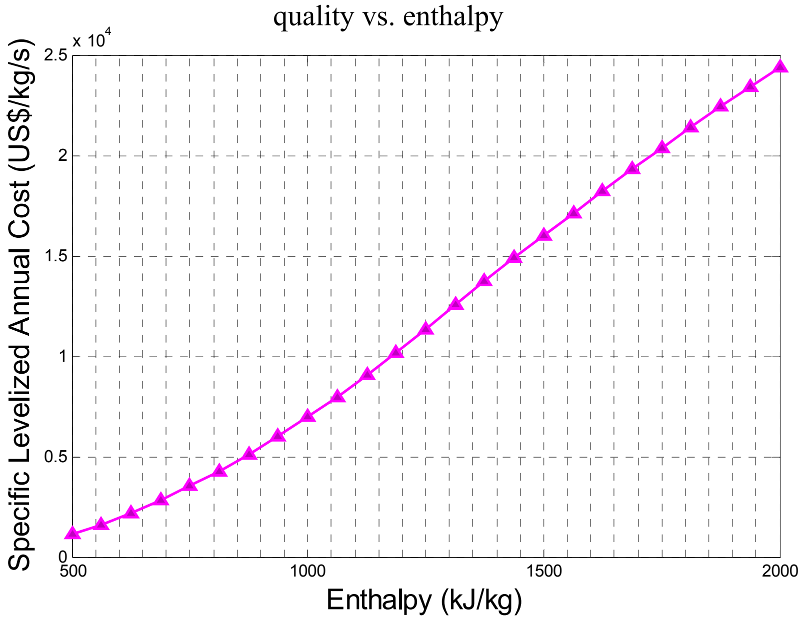

FIGURE 17: Specific levelized annual cost vs. enthalpy

The blue colour line with triangular markers represents the steam quality of the exhaust turbine of the low pressure turbine. As enthalpy increases from 500 to 1250 kJ/kg, the steam quality of the low pressure turbine exhaust decreases from 0.93 to 0.85. For enthalpy higher than 1250 kJ/kg the steam quality remained constant at 0.85 due to constraints.

The capital and O&M costs 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 17 shows the specific levelized annual cost of the combined plant at the optimum power output. As enthalpy increased from 500 to 2000 kJ/kg, the specific levelized annual cost ranged from US$ 1138 to 24,360 per kg/s mass flow.

4.1.1 Summary

This combined plant model gave significant additional specific power output to the existing single flash plant. For a given enthalpy of 500 kJ/kg, this model generated a specific power output of 17 kW per kg/s of geothermal fluid; the annual cost needed to generate this specific power output is US$ 1,138 per kg/s of geothermal fluid. For enthalpy of 2000 kJ/kg this model generated a specific power output of 364.3 kW per kg/s geothermal fluid. The specific levelized annual cost needed to generate this specific power output is US$ 24,360 per kg/s geothermal fluid.

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 18. The red colour 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 2000 kJ/kg the optimum specific power output ranges from 11.4 to 329.3 kW/kg/s.

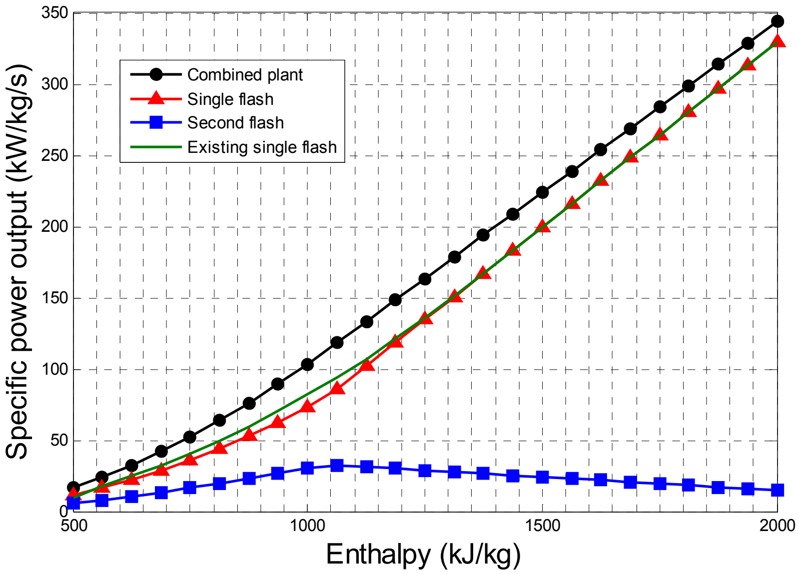

FIGURE 18: Specific power output of the combined single and second flash plant vs. enthalpy

The blue colour line with square markers represents the specific power output of a second flash plant. As enthalpy increases from 500 to 1063 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 1063 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 colour line with dot markers represents the performance of the combined plant. As enthalpy increased from 500 to 2000 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 19 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 1063 kJ/kg. Then, the optimum separation pressure remains constant at 849.1 kPa for any enthalpy higher than 1063 kJ/kg.

The optimum low pressure separation is defined as the pressure of the second separation process which gives the maximum output of the combined plant. Figure 20 shows the optimum low pressure separation for different enthalpies. The optimum low pressure separation increased from 30.2 to 127 kPa as enthalpy in-creased from 500 to 1063 kJ/kg. The separation pressure remained constant at 127 kPa as enthalpy increased from 1063 to 2000 kJ/kg due to the constraints of both turbines' exhaust steam quality.

The optimum condenser pressure was defined as the condenser pressure which gave the maximum power output of the combined plant. The results show that as enthalpy ranges from 500 to 2000 kJ/kg the optimum condenser pressure of both single flash and second flash remained a constant 8 kPa due to the lower boundary of the condenser pressure set for the optimization process.

To avoid turbine blade damage by corrosion, the steam of the turbine exhaust was set as a constraint with a minimum quality of 0.85. Figure 21 shows the steam quality of both turbines' exhaust. Both of the turbines' exhaust had exactly the same result. The steam quality was between 0.92 and 0.85 as enthalpy increased from 500 to 1063 kJ/kg. The steam quality

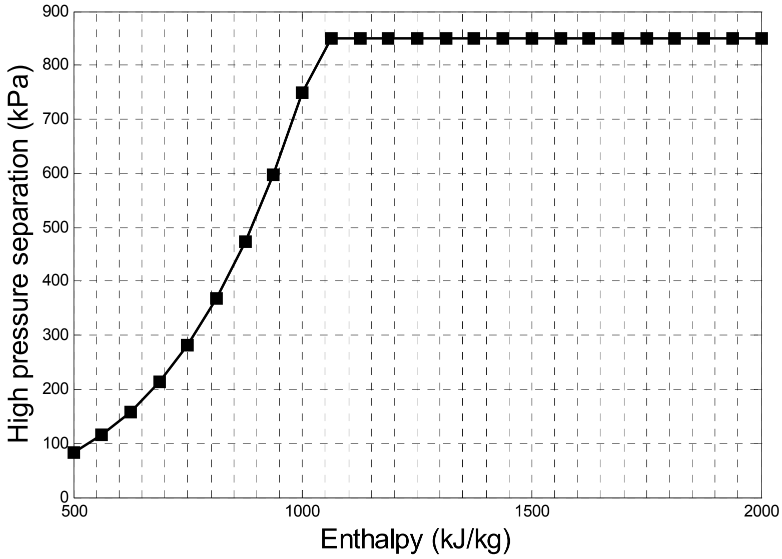

FIGURE 19: High pressure separation of a combined single and second flash plant vs. enthalpy

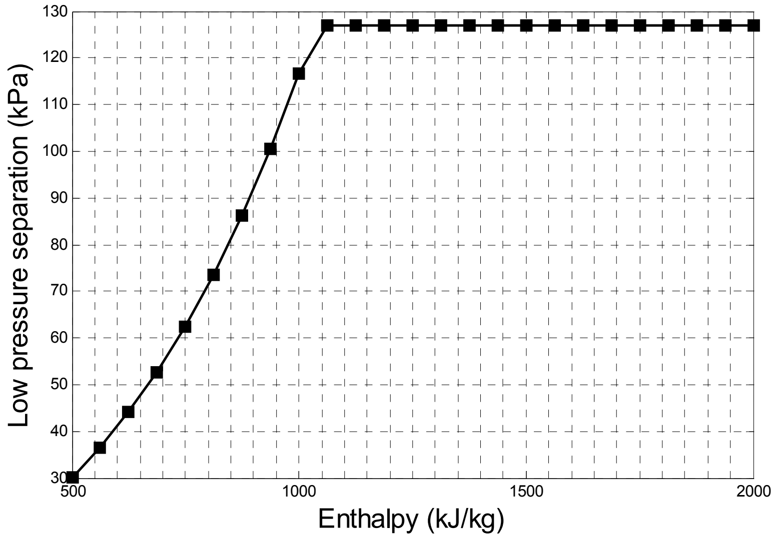

FIGURE 20: Low pressure separation of a combined single and second flash plant vs. enthalpy

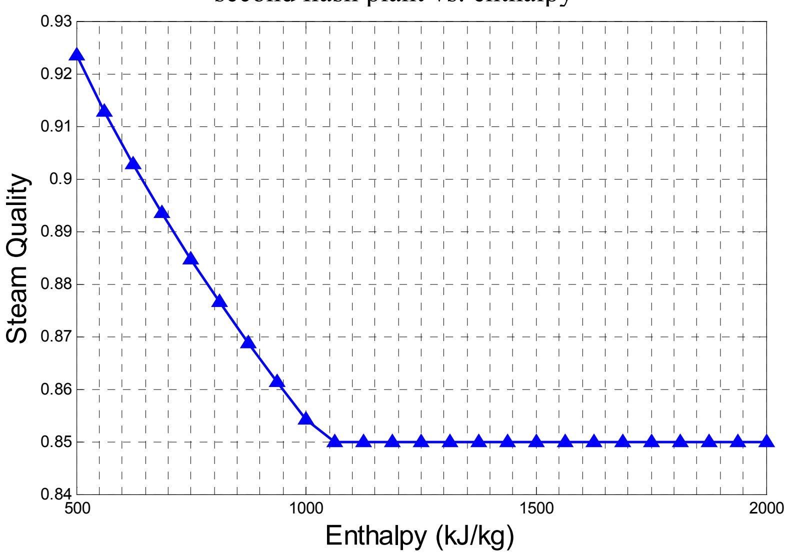

FIGURE 21: Single and second flash turbine exhaust steam quality vs. enthalpy

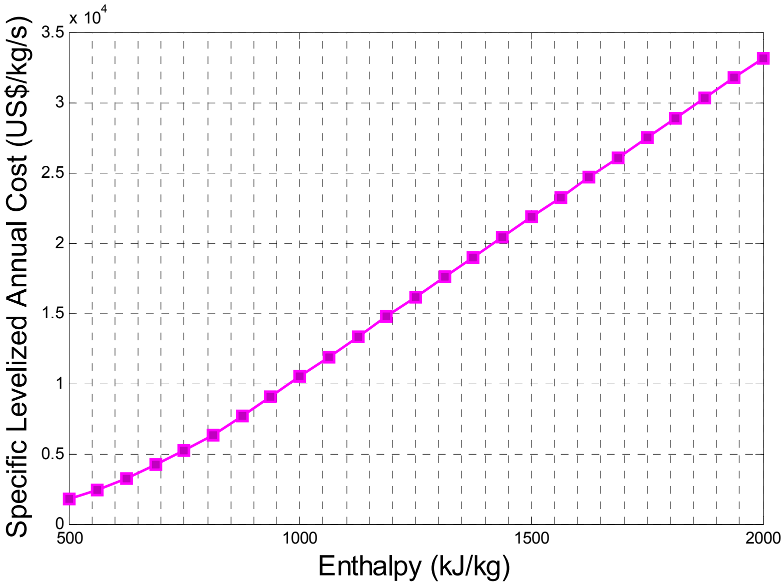

FIGURE 22: Specific levelized annual cost vs. enthalpy

became constant at 0.85 when enthalpy rose higher than 1063 kJ/kg. This was the optimum steam quality that gave the maximum power output, while keeping the turbine blades in good condition.

The capital and O&M costs were levelized and calculated annually. For this model the capital cost was assumed to be US$ 1236 per kW installed capacity and O&M cost was US$ 0.015 per kWh. Figure 22 shows the specific levelized annual cost of the combined plant with the optimum power output as installed capacity. As enthalpy increased from 500 to 2000 kJ/kg, the specific levelized annual cost increased from US$1158 to 23,240 per kg/s mass flow.

4.2.1 Summary

This combined plant model gave significant additional specific power output to the existing single flash plant. For a given enthalpy of 500 kJ/kg, this model generated a specific power output of 17.1 kW per kg/s of geothermal fluid and the annual cost that was needed to generate this specific power output was US$ 1158 per kg/s of fluid. For an enthalpy of 2000 kJ/kg, this model generated a specific power output of 344 kW per kg/s fluid. The specific levelized annual cost to generate this power output was US$ 23,240 per kg/s fluid.

4.3 The optimum specific power output of a combined single flash and ORC plant

Figure 23 shows the optimum specific power output of the combined single flash and ORC plant for various enthalpies of the geothermal fluid. The red colour 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 2000 kJ/kg, the optimum specific power output increased from 10.1 to 331.6 kW/kg/s.

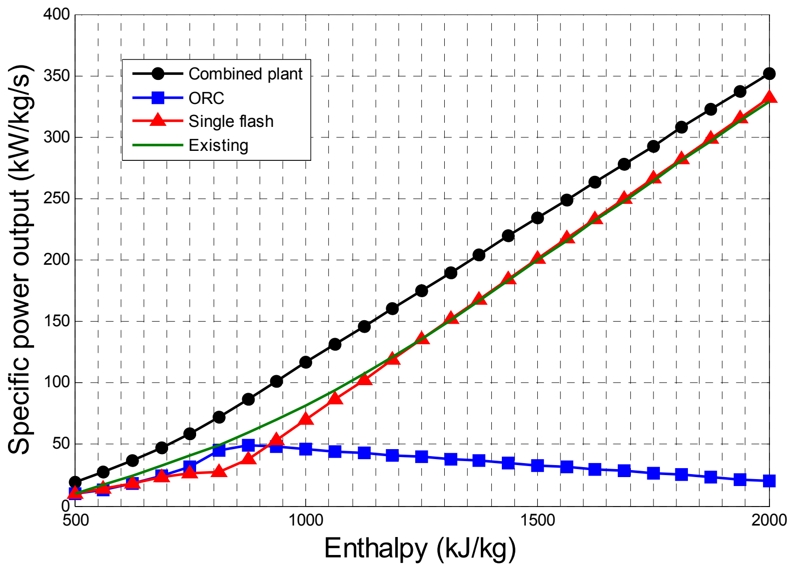

FIGURE 23: Specific power output of a combined single flash and ORC vs. enthalpy

The blue colour 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 2000 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 increased/decreased?.

The black colour line with dot markers represents the total specific power output of the combined plant. As enthalpy increased from 500 to 2000 kJ/kg, the specific power output of the combined plant increased from 19.5 to 351.7 kW/kg/s.

The optimum separation pressure is defined as the vapour and liquid separation pressure which gives the maximum specific power output of the combined plant. Figure 24 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's exhaust.

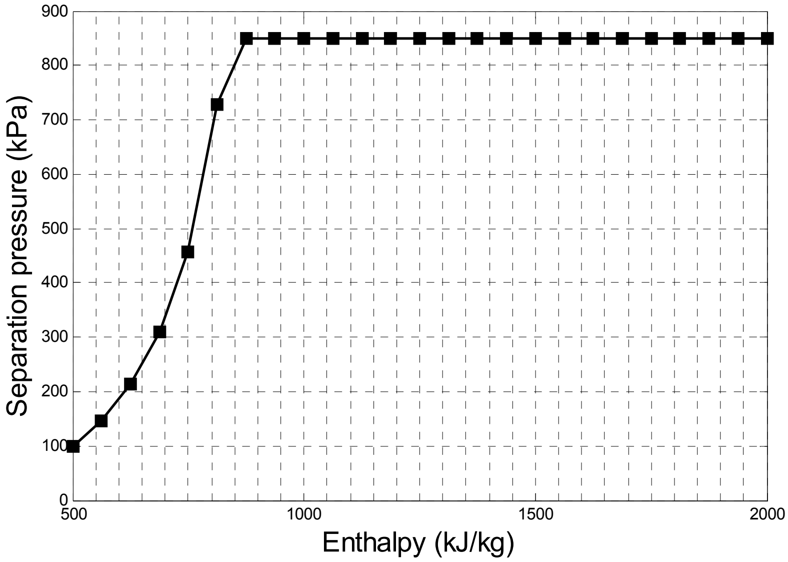

FIGURE 24: Separation pressure of a combined single flash and ORC vs. enthalpy

The optimum condenser pressure of a single flash plant is defined as the condenser pressure of a single flash plant which gave the maximum specific power output of the combined plant. The results show that when enthalpy increased from 500 to 2000 kJ/kg, the optimum condenser pressure remained constant at 8 kPa due to the lower boundary of the condenser pressure which was set for the optimization process.

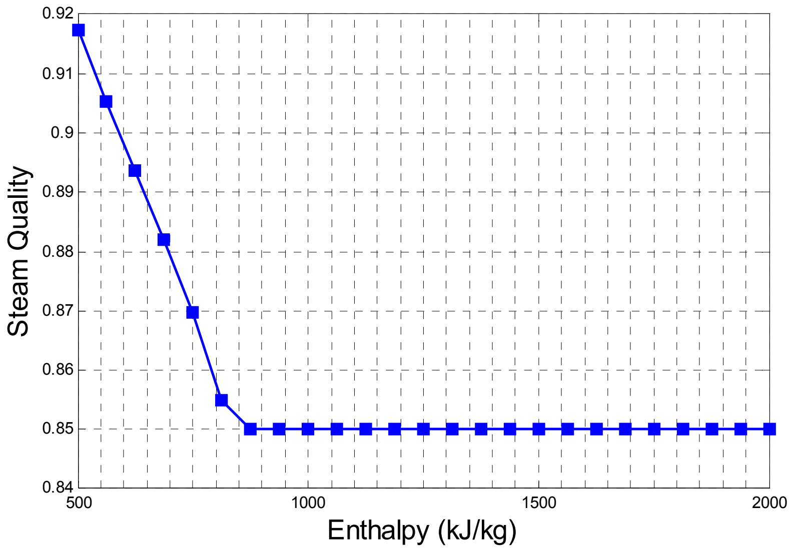

FIGURE 25: Single flash turbine exhaust steam quality vs. enthalpy

To maintain the turbine blades in good condition, the steam of the turbine exhaust was set as a constraint with a minimum quality of 0.85. Figure 25 shows the steam quality of the single flash turbine exhaust. The steam quality measured between 0.92 and 0.85 when the enthalpy increased from 500 to 875 kJ/kg. The steam quality became constant at 0.85 when the enthalpy rose higher than 875 kJ/kg. This is the optimum steam quality that gave the maximum specific power output, while keeping the turbine blades in good condition.

The optimum ORC turbine pressure is defined as the pressure of an ORC turbine which gives the maximum specific power output of the combine plant. Figure 26 shows the optimum ORC's turbine pressure for different enthalpies. The optimum ORC's turbine pressure increased from 314.4 to 854.7

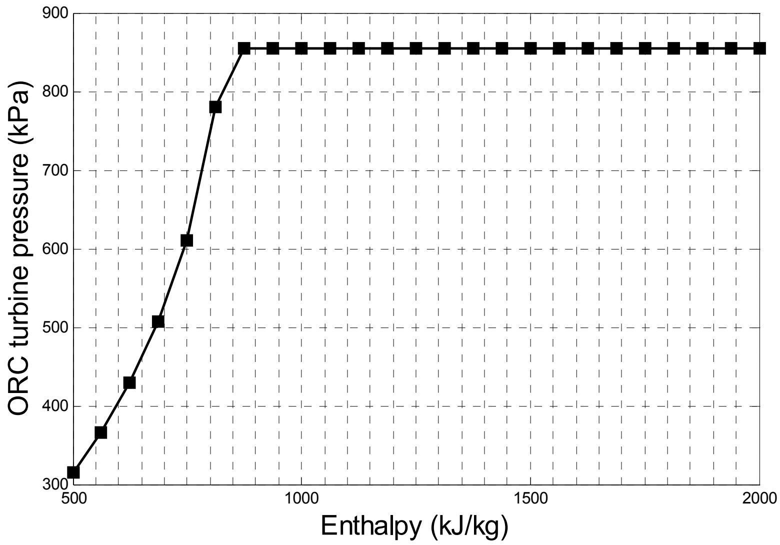

FIGURE 26: ORC turbine pressure vs. enthalpy

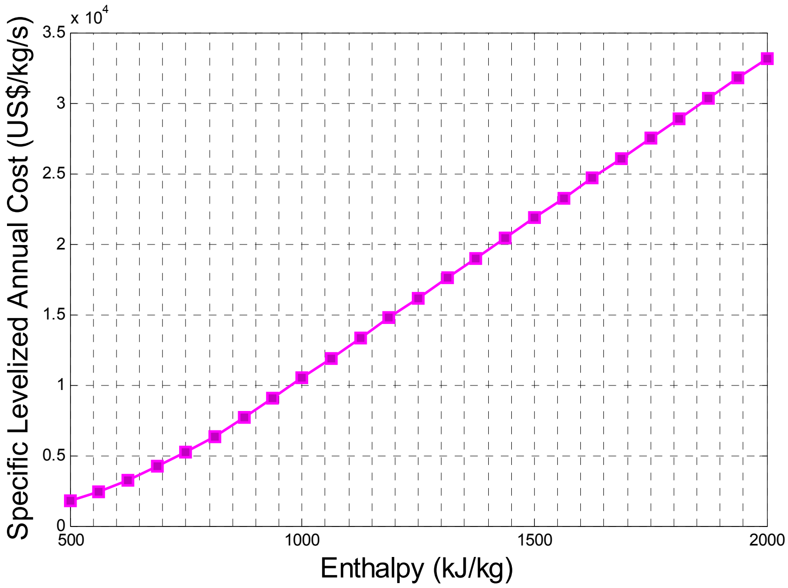

FIGURE 27: Specific levelized annual cost vs. enthalpy

kJ/kg when the enthalpy of the geothermal fluid increased from 500 to 875 kJ/kg. The optimum ORC turbine pressure remained constant at 854.7 kPa for any enthalpy higher than 875 kJ/kg, due to constraints on the steam quality of the single flash turbine's exhaust.

Figure 27 shows the specific levelized annual cost of the combined plant with the optimum specific power output as the installed capacity. As enthalpy increased from 500 to 2000 kJ/kg, the specific levelized annual cost increased from US$ 1,737 to 33,160 per kg/s mass flow. The capital costs of a single flash and ORC were assumed to be US$ 1,236 and 2,259 per kW installed capacity. The O&M costs were assumed to be US$ 0.015 and 0.02 per kWh, respectively.

4.3.1 Summary

This combined plant model gave significant additional specific power output to the existing single flash plant. For a given enthalpy of 500 kJ/kg, this model generated a specific power output of 19.5 kW per kg/s of geothermal fluid and the annual cost that was needed to generate this specific power output was US$ 1,737 per kg/s of fluid. For an enthalpy of 2000 kJ/kg this model generated a specific power output of 351.7 kW per kg/s of fluid. The specific levelized annual cost to generate this power output was US$ 33,160 per kg/s fluid.

4.4 The optimum specific power output of a combined single flash and advanced ORC plant

Figure 28 shows the optimum specific power output of the plant for various enthalpies of the geothermal fluid. The red colour 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 2000 kJ/kg, the optimum specific power output increased from 0 to 331.6 kW/kg/s.

The blue colour 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 2000 kJ/kg the optimum specific power output decreased from 71.6 to 27.31 kW/kg/s.

The black colour 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 2000 kJ/kg, the combined plant produced a 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 vapour and liquid separation pressure which gives the maximum specific power output of the combined plant. Figure 29 shows the optimum separation pressure for different enthalpies. 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 the single flash turbine's exhaust.

In order to keep the single flash turbine blades in good condition, the steam of the turbine exhaust was set as a constraint with a minimum quality of 0.85. Figure 30 shows the steam quality of the single flash turbine's exhaust. The steam quality ranged from 0.9 to 0.85 when enthalpy increased from 500 to 750 kJ/kg. The steam quality remained constant at 0.85 for enthalpies higher than 750 kJ/kg.

The optimum high pressure turbine pressure is defined as the

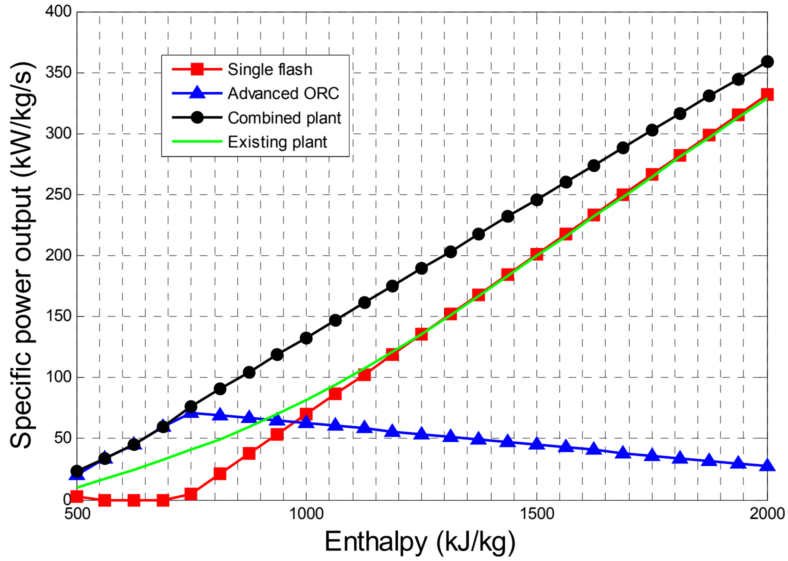

FIGURE 28: Specific power output of a combined single flash and advanced ORC vs. enthalpy

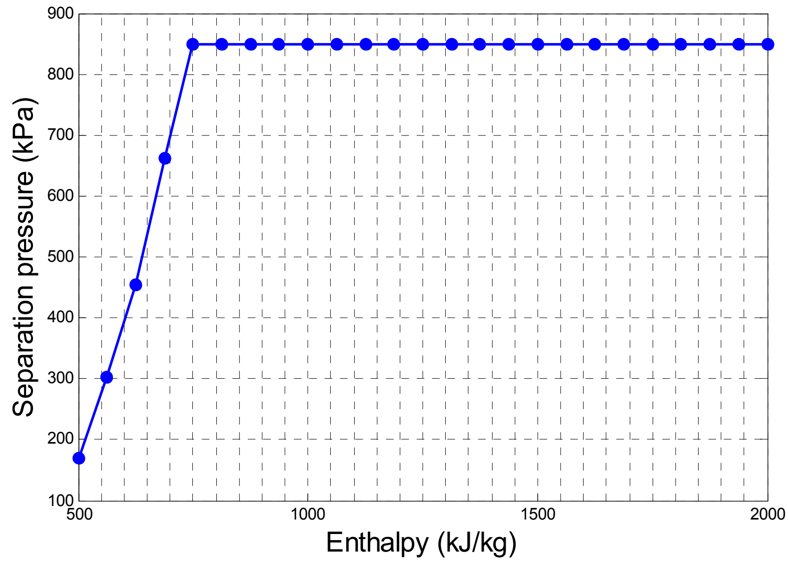

FIGURE 29: Separation pressure of a combined single flash and advanced ORC vs. enthalpy

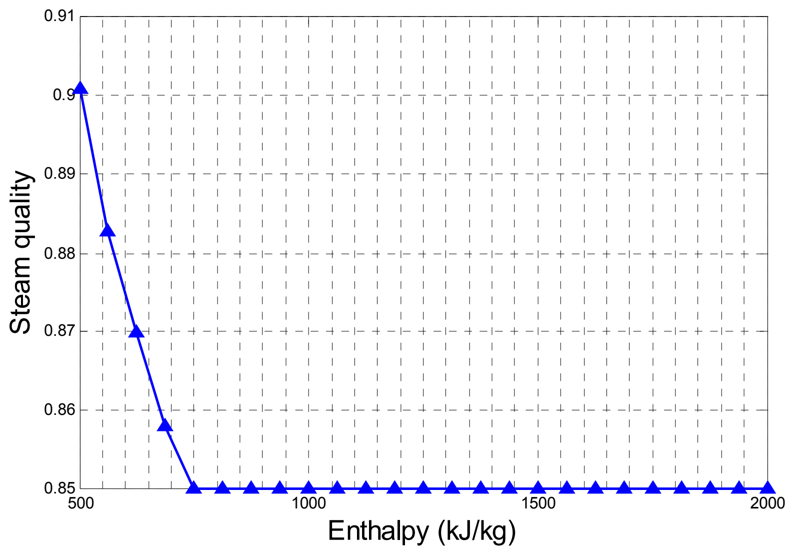

FIGURE 30: Steam quality of the single flash turbine exhaust vs. enthalpy

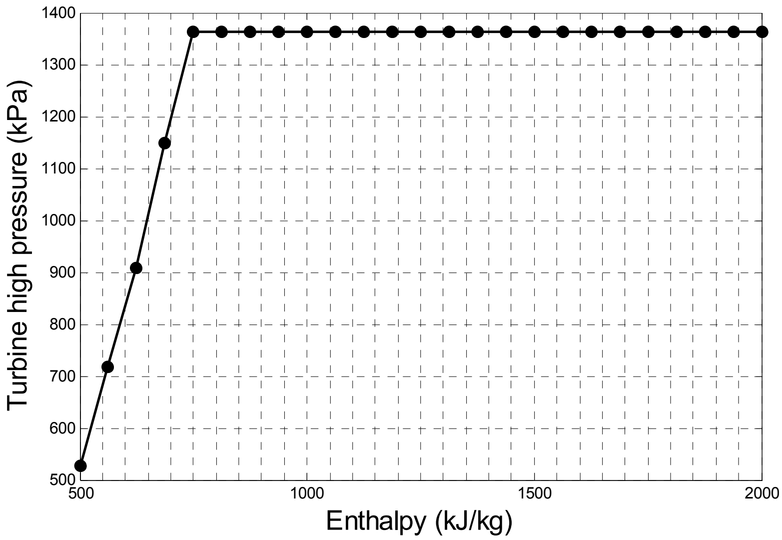

FIGURE 31: High turbine pressure vs. enthalpy

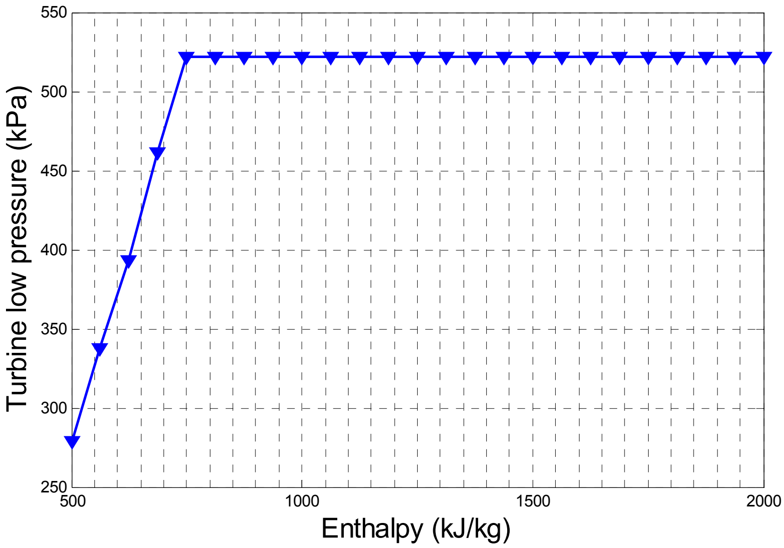

FIGURE 32: Low turbine pressure vs. enthalpy

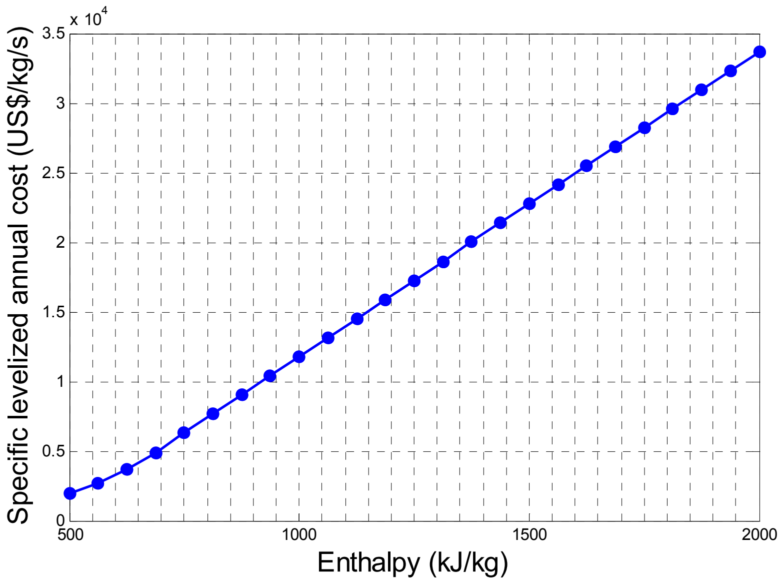

FIGURE 33: Specific levelized annual cost vs. enthalpy

pressure design of advanced ORC's high pressure turbine which gives the maximum power of the combined plant. Figure 31 shows the optimum high pressure turbine pressure for different enthalpy. The optimum high pressure turbine rose when enthalpy increased from 500 to 750 kJ/kg. The optimum separation pressure remained constant at 1363 kPa for all enthalpies higher than 750 kJ/kg, due to constraints of the steam quality of the single flash turbine's exhaust.

The optimum pressure of a low pressure turbine is defined as the pressure of an advanced ORC low pressure turbine which gives the maximum specific power output of the combine plant. Figure 32 shows the optimum pressure of a low pressure turbine for different enthalpies. The optimum pressure of a low pressure turbine increased from 279.1 to 522.2 kPa as the enthalpy increased from 500 to750 kJ/kg. Then, the optimum pressure of low pressure turbine remained constant at 522.1 kPa for all enthalpies higher than 750 kJ/kg, due to constraints of the steam quality of a single flash turbine's exhaust.

Figure 33 shows the specific levelized annual cost of the combined plant with the optimum output power as the installed capacity. As enthalpy increased from 500 to 2000 kJ/kg, the specific levelized annual cost ranged from US$ 1,937 to 33,720 per kg/s fluid. The capital costs of a single flash and advanced ORC plant were assumed to be US$ 1236 and 2374 per kW installed capacity. The O&M costs were assumed to be US$ 0.015 and 0.02 per kWh, respectively.

4.4.1 Summary

This combined plant model gave significant additional specific power output to the existing single flash plant. For a given enthalpy of 500 kJ/kg, this model generated a specific power output of 23.4 kW per kg/s of fluid and the annual cost needed to generate this specific power output was US$ 1937 per kg/s of fluid. For an enthalpy of 2000 kJ/kg this model generated a specific power output of 360.5 kW per kg/s fluid. The specific levelized annual cost needed to generate this power output was US$ 33,720 per kg/s fluid.

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 34 were definitely not good, even though this study attempts to find the reason why for future study.

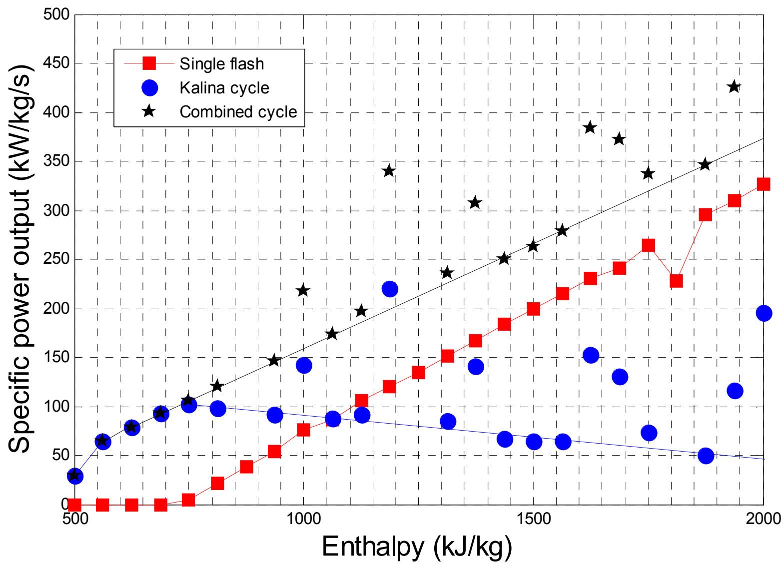

FIGURE 34: Specific power output of a combined single flash and Kalina cycle vs. enthalpy

Figure 34 shows the optimum specific power output of the plant at various enthalpies of geothermal fluid. The red line with squares represents the single flash plant's specific power output. The figure seems to be on the correct trend where the specific power output increases as the enthalpy increases from 500 to 2000 kJ/kg. However, at one point, for an enthalpy of 1818 kJ/kg, the result went lower than expected.

The blue dots represent the specific power output of a Kalina cycle for a given enthalpy range of 500 to 2000 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's specific power output. The incorrect results float above the blue line.

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

The correct trends of the single flash and Kalina cycle indicated 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 database. The database, 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 database should be addressed.

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

4.5.1 Summary

The study was not successful in determining the specific power output for enthalpies ranging from 500 to 2000 kJ/kg, even though the study was successful in identifying the problems faced by the simulation. This study identified an insufficient ammonia-water mixture property in the REFPROP database. The study also found that the built-in optimization tool in the MATLAB software was not sufficient to optimize the Kalina cycle due to a lag on the database. A global evolutionary search technique was thought to give a better solution.

4.6 The percentage of additional specific power output of the combined plants

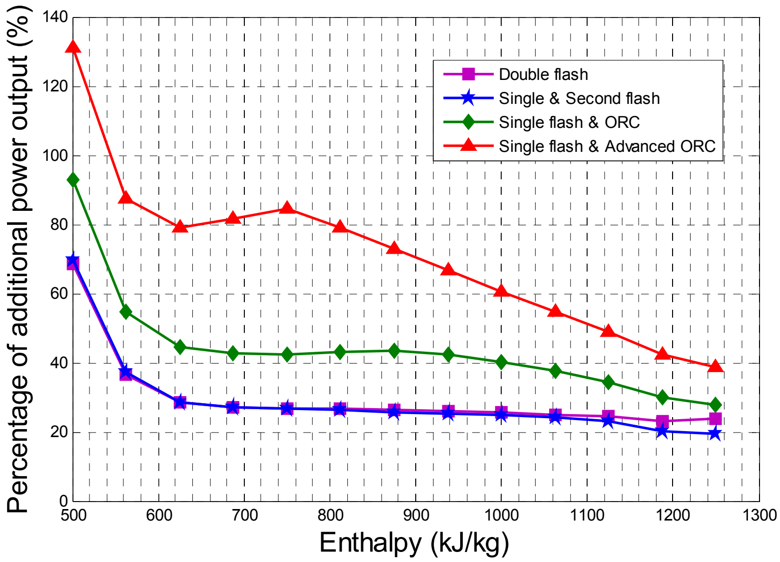

FIGURE 35: The percentage of additional specific power output of combined plants vs. enthalpy

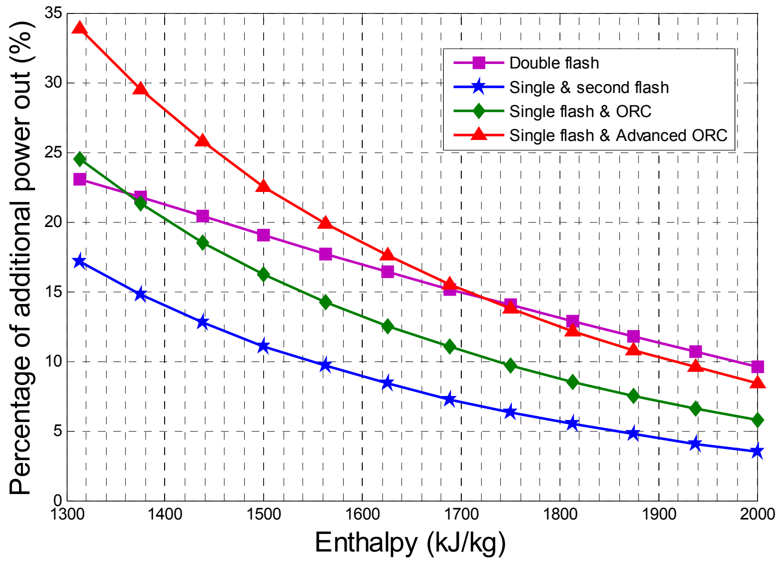

FIGURE 36: The percentage of additional specific power output of combined plants vs. enthalpy kJ/kg, the double flash plant gave the highest additional specific power output.

The percentage of additional specific power outputs of the combined plants is shown in Figure 35. As the enthalpy ranged between 500 and 1250 kJ/kg, the combined single flash and advanced ORC plant gave the highest percentage of additional specific power output.

Figure 36 shows the percentage of specific power outputs of the combined plants vs. enthalpy ranging from 1313 to 2000 kJ/kg. For enthalpy ranging from 1313 to 1700 kJ/kg the combined single flash and advanced ORC plant produced the highest additional specific power output. For enthalpy ranging from 1,700 to 2000 kJ/kg, the double flash plant produced higher specific power output.

For enthalpy ranging from 500 to 2000 kJ/kg, the percentage of specific power outputs of all the modelled plants is summarized in Table 7.

A comparison of optimum high separation pressure of the combined plants is shown in Figure 37. The double flash plant has the highest range of optimum separation pressure from 80.8 to 1937 kPa for enthalpy ranging from 500 to 2000 kJ/kg.

TABLE 7: The percentage of additional specific power outputs

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

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 1500 kJ/kg. The operator of the field plans to utilize the fluid of the wells for maximum power output.

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?

The results of this study can be used to answer these questions quickly and easily. Figure 36 shows that with an enthalpy of 1500 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 1500 kJ/kg is 247 kW/kg/s, as shown in Figure 28.

Figure 37 shows that for an enthalpy of 1500 kJ/kg, the optimum separation pressure for combined plant is 849.1 kPa. From the 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 supposedly produces 100 kg/s of geothermal fluid. By multiplying 100 kg/s by 247 kW/kg/s, the combined single flash and Advanced ORC plant will produce 24.7 MW.

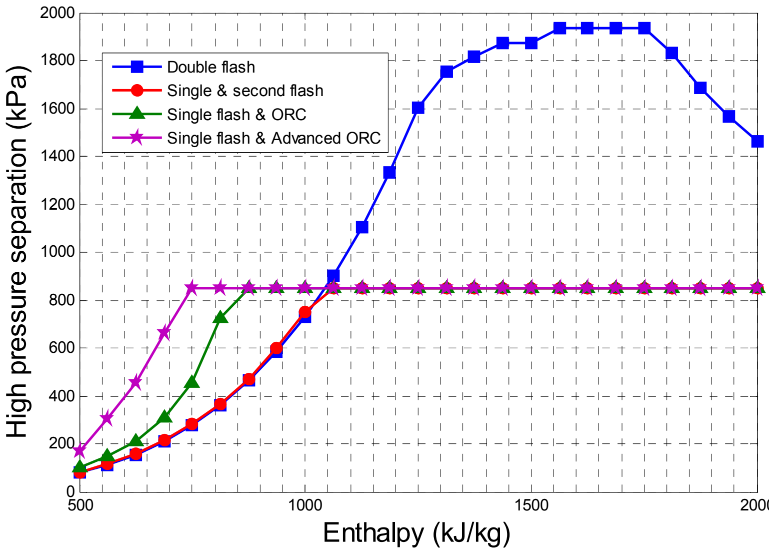

FIGURE 37: Comparison of separation pressures of different combined plants vs. enthalpy power generation

If the field operator has decided to install a combined single and second flash plant due to its simplicity and reliability, this guide can be used easily by using Figure 36. The blue line gives the information needed: if the enthalpy of the fluid is 1500 kJ/kg then the percentage of the specific power output of a single and second flash plant is 11%. The specific power output of the combined plant for enthalpy of 1500 kJ/kg is 223.7 kW/kg/s, shown in Figure 18. The red line on Figure 37 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. CONCLUSIONS

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 2000 kJ/kg. The specific levelized annual cost ranged from US$ 1138 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 2000 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 2000 kJ/kg. The specific levelized annual cost ranged from US$ 1158 to 23,240 per kg/s. This combined plant had the lowest additional specific power output. For the enthalpy range from 500 to 2000 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 2000 kJ/kg. The specific levelized annual cost ranged from US$ 1737 to 33,160 per kg/s. For enthalpy ranging from 500 to 2000 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 2000 kJ/kg. The specific levelized annual cost to generate the optimum specific power output ranged from US$ 1937 to 33,720 per kg/s. For enthalpy ranging from 500 to 1700 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 database 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 database should be addressed.

The results of this study can be used as a fast and easy guide to determine the specific power output from four models of combined power plants. It can be used as a reference not only for new fields which plan to install a combined plant where a single flash cycle plant is the main plant but also for the field in which a single flash plant is 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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