Makara Journal of Technology

Volume 19 | Number 1 Article 8

4-1-2015

Energy and Exergy Analysis of Kalina Cycle for the Utilization of Waste Heat in Brine Water for Indonesian Geothermal Field

Nasruddin Nasruddin
Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia, nasruddin@eng.ui.ac.id

Agus Noor Sidiq
Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia

Abdulmajeed Mohamad
Department of Mechanical and Manufacturing Engineering, Schulich School of Engineering, The University of Calgary, Calgary, AB, T2N 1N4, Canada

Rama Usvika
PT. Rekayasa Industri, Jakarta 12740, Indonesia

Makara J. Technol. 19/1 (2015), 38-44
doi: 10.7454/mst.v19i1.3032

Energy and Exergy Analysis of Kalina Cycle for the Utilization of Waste Heat in Brine Water for Indonesian Geothermal Field

Nasruddin[1*], Agus Noor Sidiq[1], Abdulmajeed Mohamad[2], and Rama Usvika[3]

1. Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia
2. Department of Mechanical and Manufacturing Engineering, Schulich School of Engineering, The University of Calgary, Calgary, AB, T2N 1N4, Canada
3. PT. Rekayasa Industri, Jakarta 12740, Indonesia

[*]*e-mail: nasruddin@eng.ui.ac.id*

Abstract

The utilization of waste heat in a power plant system—which would otherwise be released back to the environment—in order to produce additional power increases the efficiency of the system itself. The purpose of this study is to present an energy and exergy analysis of Kalina Cycle System (KCS) 11, which is proposed to be utilized to generate additional electric power from the waste heat contained in geothermal brine water available in the Lahendong Geothermal power plant site in North Sulawesi, Indonesia. A modeling application on energy and exergy system is used to study the design of thermal system which uses KCS 11. To obtain the maximum power output and maximum efficiency, the system is optimized based on the mass fraction of working fluid (ammonia-water), as well as based on the turbine exhaust pressure. The result of the simulation is the optimum theoretical performance of KCS 11, which has the highest possible power output and efficiency. The energy flow diagram and exergy diagram (Grassman diagram) was also presented for KCS 11 optimum system to give quantitative information regarding energy flow from the heat source to system components and the proportion of the exergy input dissipated in the various system components.

Abstrak

Analisis Energi dan Eksergi Siklus Kalina untuk Pemanfaatan Limbah Panas di dalam Air Garam untuk Ladang Panas Bumi Indonesia. Pemanfaatan limbah panas pada sistem pembangkit tenaga listrik, yang sebetulnya akan dikembalikan ke alam, untuk memproduksi tambahan tenaga listrik akan meningkatkan keefisienan sistem itu sendiri. Penelitian ini bertujuan untuk menampilkan analisis energi dan eksergi Sistem Siklus Kalina (*Kalina Cycle System* atau KCS) 11 yang kami ajukan agar dapat dimanfaatkan untuk menghasilkan tenaga listrik tambahan dari limbah panas yang terkandung di dalam air garam panas bumi yang terdapat di situs pembangkit listrik tenaga Panas Bumi Lahendong, Sulawesi Utara, Indonesia. Penerapan model sistem energi dan eksergi digunakan untuk mengkaji rancangan sistem termal yang menggunakan KCS 11. Untuk menghasilkan keluaran tenaga listrik yang maksimal dan keefisienan yang maksimal, sistem itu akan dioptimalkan berdasarkan fraksi massa cairan yang digunakan (air amonia) dan tekanan keluar turbin. Simulasi ini menghasilkan performa KCS 11 yang optimal secara teoretis, yang menunjukkan keluaran tenaga listrik dan keefisienan yang paling tinggi. Diagram aliran energi dan diagram eksergi (diagram Grassman) juga disajikan di dalam sistem KCS 11 yang telah dioptimalkan itu untuk menyediakan informasi kuantitatif tentang aliran energi dari sumber panas menuju komponen-komponen sistem dan tentang proporsi masukan eksergi yang tersebar di berbagai komponen dalam sistem itu.

Keywords: exergy, geothermal brine, Kalina cycle, optimization

1. Introduction

Indonesia has abundant geothermal resources that can be used for power generation and other energy-related applications. Official data shows that the total Indonesian geothermal resources are 27,000 MWe; which means that it can generate up to 27 GW of electricity. This is one of the biggest resources in world.

Geothermal resources, once it is explored and brought up to the earth surface, usually produce medium pressure steam in saturated condition. The steam can be used to generate electricity in a steam turbine generator, and then the condensing liquid is injected back to the earth inner surface for maintaining the geothermal reservoir.

The steam conditions vary from one site to another. Some of the geothermal resources that have been exploited in Indonesia produce a dry steam fluid (having very low water content); while others produce wet steam fluid, with a high two-phase saturated steam condition. In the case of wet steam, the water content in the two-phase fluid flow must be separated in a separator, where the steam can proceed to the power station, and the brine water, as the result of separation process, is normally discharged back to the well. Since the separation process does not cool down the geothermal stream significantly, the brine water still has high temperature, which shows its potential as additional energy source. If this brine water is not used further by any means, then the potential heat energy in the brine water would be wasted.

This paper studies the possibility of using Kalina Cycle KCS 11 system for utilization of waste heat in geothermal brine water to generate electricity. KCS11 is one of the many variant of Kalina cycle patented by Alexander Kalina, its inventor. It was found at the initial investigation that KCS11 is the most suitable cycle to be applied for geothermal site condition in Indonesia.

The geothermal resources in Lahendong site, located in the northern part of Sulawesi Island, Indonesia, produces steam and brine water from the outlet of separator as shown in Table 1 below.

This study proposes KCS 11 to be used as the bottoming cycle in LHD-5 Geothermal Power Plant in Lahendong, North Sulawesi, Indonesia. This cogeneration system will be used to produce more power from the waste heat of geothermal brine before the brine water is injected back to the earth. It has been calculated that the pressure losses in the brine separator would be 0.5 bar and thus temperature decrease of brine water is about 2 °C.

Table 1. Geothermal Data from LHD-5 field at Lahendong Geothermal Site

Geothermal fluid parameters	LHD-5
Wellhead Pressure (bar)	10.7
Enthalpy (kJ/kg)	1160
Temperature (^{0}C)	182
Dryness (%)	20
Total flow (kg/s)	63
Steam flow (kg/s)	12
Water flow (kg/s)	51

2. Methods

System description. The proposed KCS 11 to be utilized as bottoming cycle in the Lahendong Geothermal Power Plant, North Sulawesi, Indonesia, can be seen in Figure 1 below. This system has been reviewed and analyzed using *Cycle Tempo* software from TU Delft.

The description about the system of KCS 11 is as follows: the initial working fluid of ammonia water as a saturated liquid comes out from ammonia condenser with mass fraction of basic mixture. The liquid is then pumped to the LT Recuperator, and in the LT Recuperator the fluid is heated by the working fluid that comes out from the turbine. After flowing through LT Recuperator the fluid is split into two streams. The first stream goes to HT Recuperator, and the second stream goes to the second Evaporator. In the HT Recuperator the fluid is heated again until reaching saturated vapor condition; whereas in the second Evaporator the fluid is heated by the brine water until reaching a fully saturated vapor. Then, the mass flow of working fluid from the second Evaporator and HT Recuperator is mixed into one fluid stream before entering the first Evaporator. In the first Evaporator the working fluid is heated by the brine water until reaching superheated steam condition. This hot steam flow of ammonia-water mixture containing 100% vapor phase goes through the vapor turbine to produce electric power in the AC Generator. The ammonia-water mixture that comes out from the turbine is utilized further as a heating fluid in the LT Recuperator and HT Recuperator in order to preheat the ammonia-water mixture, which has a rich liquid phase coming out from the ammonia condenser. After passing through the LT and HT Recuperator the working fluid is collected in the drain tank before finally going into the ammonia condenser. The drain tank functions as a flash tank to separate the vapor phase and liquid phase of the working fluid. The vapor stream of working fluid goes into the inlet of Ammonia condenser and undergoes a condensing process back into the liquid phase, while the liquid stream from the Drain Tank is sprayed into the condenser to increase condensation efficiency. The process is then repeated as a cycle [1].

Assumption used in the analysis. Figure 1 shows the schematic diagram of the proposed KCS 11 to be used as the bottoming cycle in the Lahendong Geothermal Power Plant, North Sulawesi, Indonesia, which uses ammonia-water mixture as a working fluid. For the purpose of analysis the following assumptions and constraints are made: (a) The system is in steady state, (b) Temperature and pressure of brine water is 180 °C and 10.2 bar, (c) Temperature and pressure cooling water is 23 °C and 3 bar, (d) High temperature difference in Evaporator -1, DLTH = 5 °C, (e) Secondary stream fluid comes out from condenser is fully saturated liquid (vapor quality = 0), (f) The discharge pressure of the ammonia

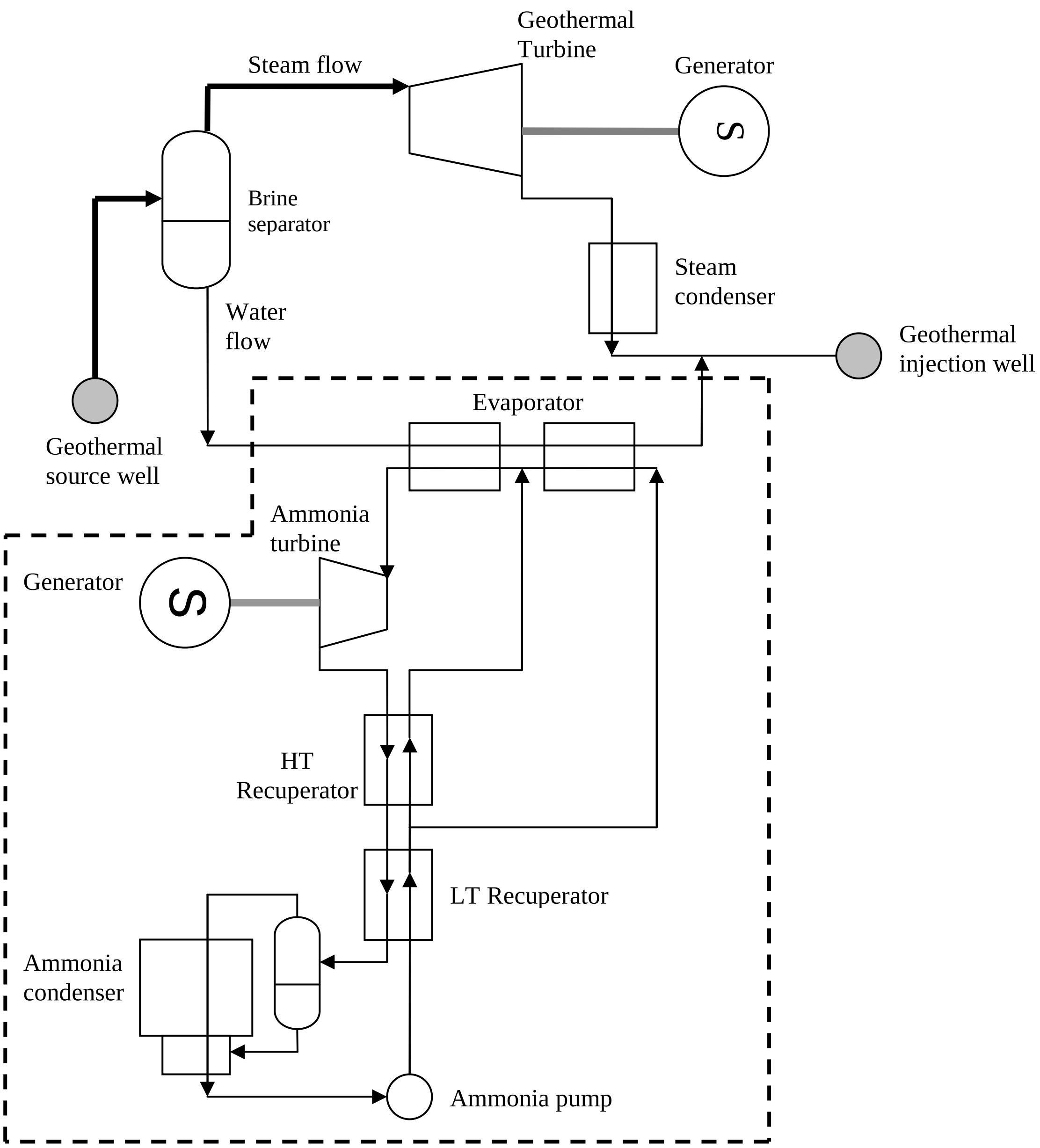

Figure 1. Schematic Diagram of KCS 11

condensate pump is 35 bar, (g) Low temperature difference in the condenser, Delta TL condenser 0< DLTL ≤ 4 °C, (h) Pressure drop in the heat exchanging equipment except secondary stream in the condenser = 0.5 bar, (i) Mixing temperature from the two stream HT Recuperator and Evaporator 2 must be less than the outlet temperature of the secondary stream Evaporator 1 to avoid the *temperature-cross* in the heat exchanger.

The optimum KCS 11 is obtained by optimizing the exhaust pressure of the turbine according to the assumption and constraint above.

Theoretical Analysis. The mass, energy, and exergy balances are used to make a system model in the Cycle Tempo software in each component of the system. The optimization procedure is executed for the maximum power output in the turbine.

The energy and exergy analysis are used to understand and study the performance of KCS 11 as a bottoming cycle. The energy and exergy balances will be used in each various apparatuses or components in the system.

Energy analysis. The general equation for energy balance is

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \quad (1)$$

the mass balance can be expressed in rate form as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (2)$$

Exergy analysis. Exergy is defined as the maximum possible reversible work obtainable in bringing the state of a system to equilibrium with that of environment [2]. The total exergy of a system becomes the summation of physical exergy and chemical exergy since there are in absence of magnetic, electric, nuclear, and surface tension effects and considering the system is at rest relative to the environment.

$$\dot{E} = \dot{E}^{ph} + \dot{E}^{ch} \quad (3)$$

The physical exergy component is calculated using the following relation:

$$\dot{E}^{ph} = \dot{m}[(h - h_0) - T_0(s - s_0)] \quad (4)$$

The calculation procedure of the chemical exergy of various substance based on standard chemical exergy values of respective species has been discussed by Bejan et al [2], Ahrendts [3]. For the analysis of KCS 11 considered here, the chemical exergy of the flows is calculated using the following equation:

$$\dot{E}_i^{Ch} = \dot{m}_i \left[\left(\frac{z_i}{M_{NH_3}} \right) e^0{}_{Ch,NH_3} + \left(\frac{1 - z_i}{M_{H_2O}} \right) e^0{}_{Ch,H_2O} \right] \quad (5)$$

Where $e^0{}_{Ch,NH_3}$ and $e^0{}_{Ch,H_2O}$ are the standard chemical exergy of ammonia and water respectively, and their values are taken from Ahrendts [3].

Exergy balance in the heat exchanging equipment and drain tank is described as:

$$\sum_{in} e_i \dot{m}_i - \sum_{exit} e_e \dot{m}_e = \dot{I}_h \quad (6)$$

Exergy balance in the turbine :

$$\sum_{in} e_i \dot{m}_i - \sum_{exit} e_e \dot{m}_e = \dot{W}_{act} + \dot{I}_t \quad (7)$$

Exergy balance in a pump:

$$\sum_{in} e_i \dot{m}_i - \sum_{exit} e_e \dot{m}_e - \dot{W}_{input} = \dot{I}_p \quad (8)$$

Power generated in the generator expressed

$$P_{gen} = P_{turbin} . \eta_{m,gen} \quad (9)$$

Where η_m is a mechanical efficiency in the turbine. Efficiency exergy is expressed as:

$$\eta_{ex,gross} = \frac{P_{gen}}{E_{absob1} + E_{absorb2}} \quad (10)$$

3. Results and Discussion

The optimum system is obtained by understanding the constraint and the objective function analyzed using Cycle Tempo software. The analysis using Cycle Tempo simulated variations of mass fractions and exhaust pressure of the turbine. Each variation of mass fraction in one set of mass fraction range has an optimal turbine exhaust pressure values. The optimum value is obtained on the turbine exhaust pressure that provides the biggest power output for the system as objective function. This approach is selected since one of the most ultimate goals of any power generation installation is to maximize the power output delivered by the power generation equipment (e.g: turbine and generator). For the same types of power station in considerations, more power output that can be generated would deliver more electricity to be sold, and thus increase the economical benefit of the installations, such as lower generation cost, increase of revenue, and shorter payback period.

A relationship between power output and the variations of ammonia mass fraction in the ammonia-water mixture (the working fluid) is described in Figure 2. The graph in Figure 2 shows that the maximum power output is obtained with 83.5% ammonia mass fraction and 9.2 bar turbine exhaust pressure. Anything below that causes the system to be against the constraint.

The power output range before optimization and after optimization is increased by lowering the ammonia mass fraction. This means for the higher mass fraction of ammonia the turbine exhaust pressure 9.9 bar is close

Table 2. Mass Fraction and Optimum Turbine Exhaust Pressure

Mass fraction ammonia (%)	Pressure before optimization (bar)	Optimum turbine exhaust pressure (bar)
83.5	9.9	9.2
84	9.9	9.2
84.5	9.9	9.3
85	9.9	9.3
85.5	9.9	9.4
86	9.9	9.5
86.5	9.9	9.5
87	9.9	9.6
87.5	9.9	9.7
88	9.9	9.7
88.5	9.9	9.8

to the optimum value number. The exergy analysis can explain why the optimization procedure takes place in the turbine not in the other apparatus in the system. Most of the exergy losses or irreversibilities take place in the turbine, and this is the biggest losses compared with other components. This high exergy losses is mainly caused by isentropic efficiency and, to the lower extent by mechanical efficiency. The exergy flow diagram or Grassman diagram in Figure 3 explained the exergy flow and also exergy losses in each component in the system KCS 11.

The Grassman diagram above shows exergy flow in the KCS 11 in the optimal condition. Apparatuses are denoted in Roman numerals. Number I is Evaporator 1; number II is turbine; number III is a mixer; number IV is Evaporator 2; number V is HT Recuperator; number VI is splitter; number VII is LT Recuperator; number VIII is a pump; number IX is a drain tank; and number X is condenser. All the unit is in kW. The losses in heat exchanging equipment such as apparatuses number I,IV,V,VII and X are caused by pressure drop.

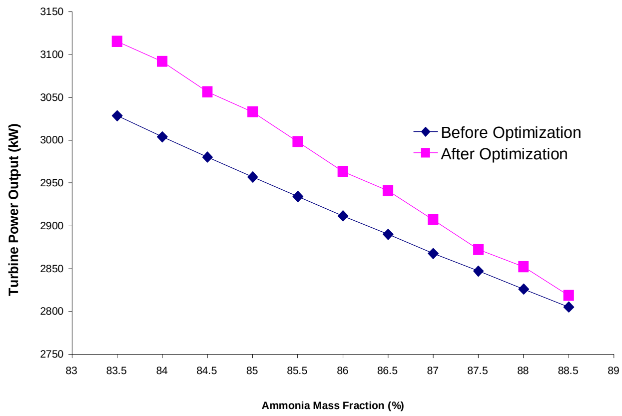

Figure 2. Turbine Power Output

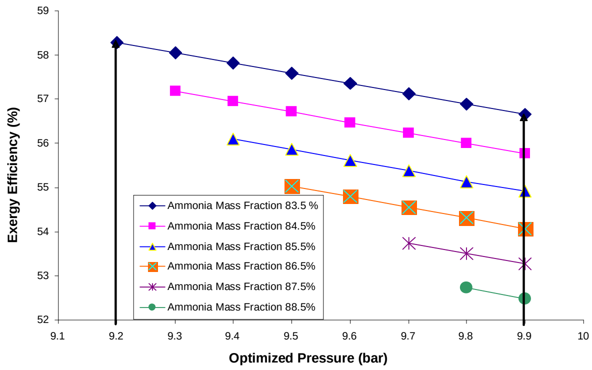

Figure 4. Exergy Efficiency

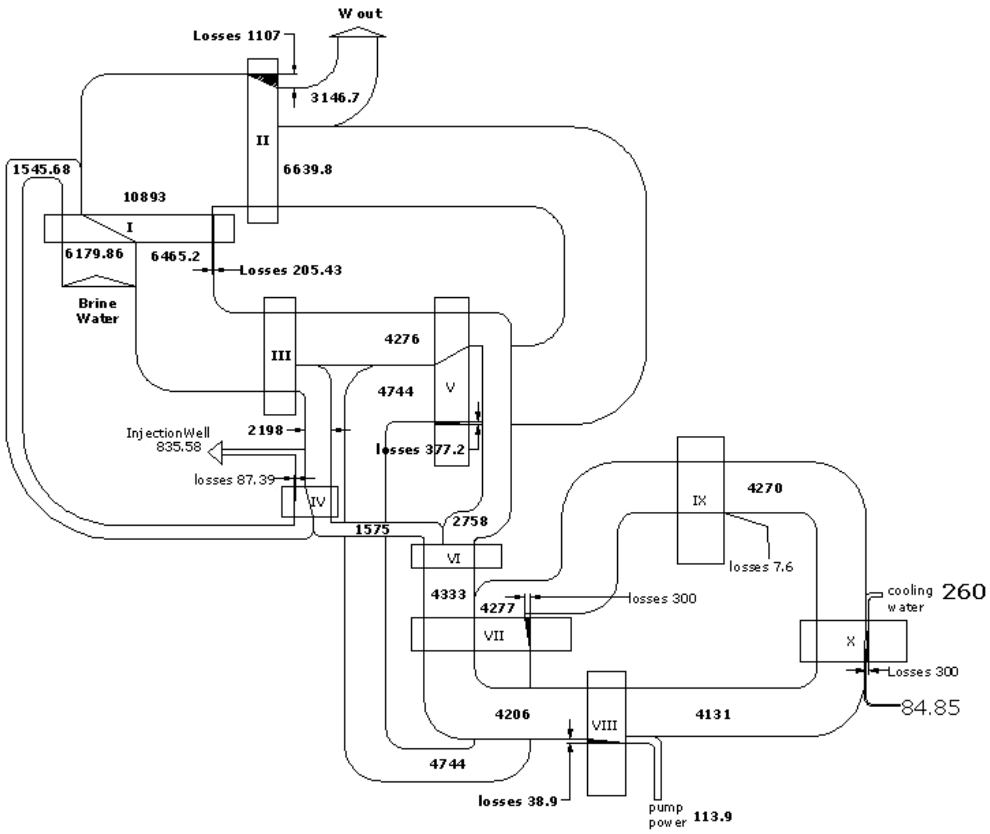

Figure 3. Physical Exergy Diagram KCS 11 for Optimal Condition

Figure 4 describes the relationship between gross exergy efficiency and turbine exhaust pressure for various ammonia mass fractions in the working fluid.

Referring to Figure 4, for a specific ammonia mass fraction in consideration, the optimum conditions would the one that results in the highest exergy efficiency. The highest exergy efficiency is obtained at the lowest possible turbine exhaust pressure. This is due to the fact that the highest irreversibilities occur in the turbine, so the turbine is the most critical part to be optimized compared to other apparatuses. However, the turbine exhaust pressure itself can not be set as low as possible due to some inherent constraints in the condenser design, cooling water inlet temperature and cooling water temperature rise. The last two factors are closely related to the environmental conditions where the installation takes place.

Figure 5 describes the relationship between exergy losses and turbine exhaust pressure for various ammonia mass fractions in the working fluid. In the same mass fraction line, we can see that for the bigger exhaust pressure the exergy losses is getting lower; this is caused by the decreasing entropy production in the turbine. Figure 5 explains the consequences that must be taken to determine the correct parameter for the turbine.

The increasing of the entropy causes the increasing of the irreversibility/losses.

Figure 6 describes the KCS 11 optimum conditions. The diagram shows that the system can produce theoretical electric power of 3115 kW in the turbine generator. The pumping power for working fluid is about 114 kW, and the pumping power for the cooling water circulation is 186 kW. Thus, the net power produced by the system should be 2815 kW.

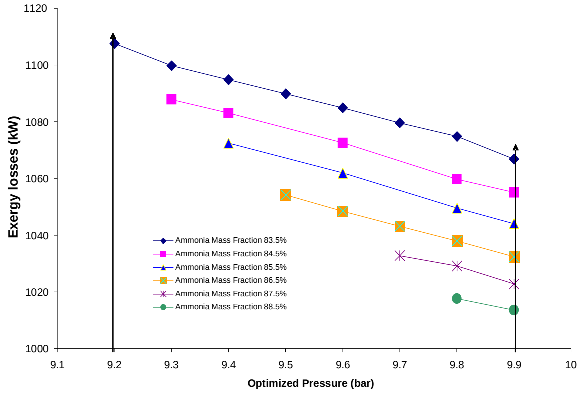

Figure 5. Exergy Losses in the Turbine

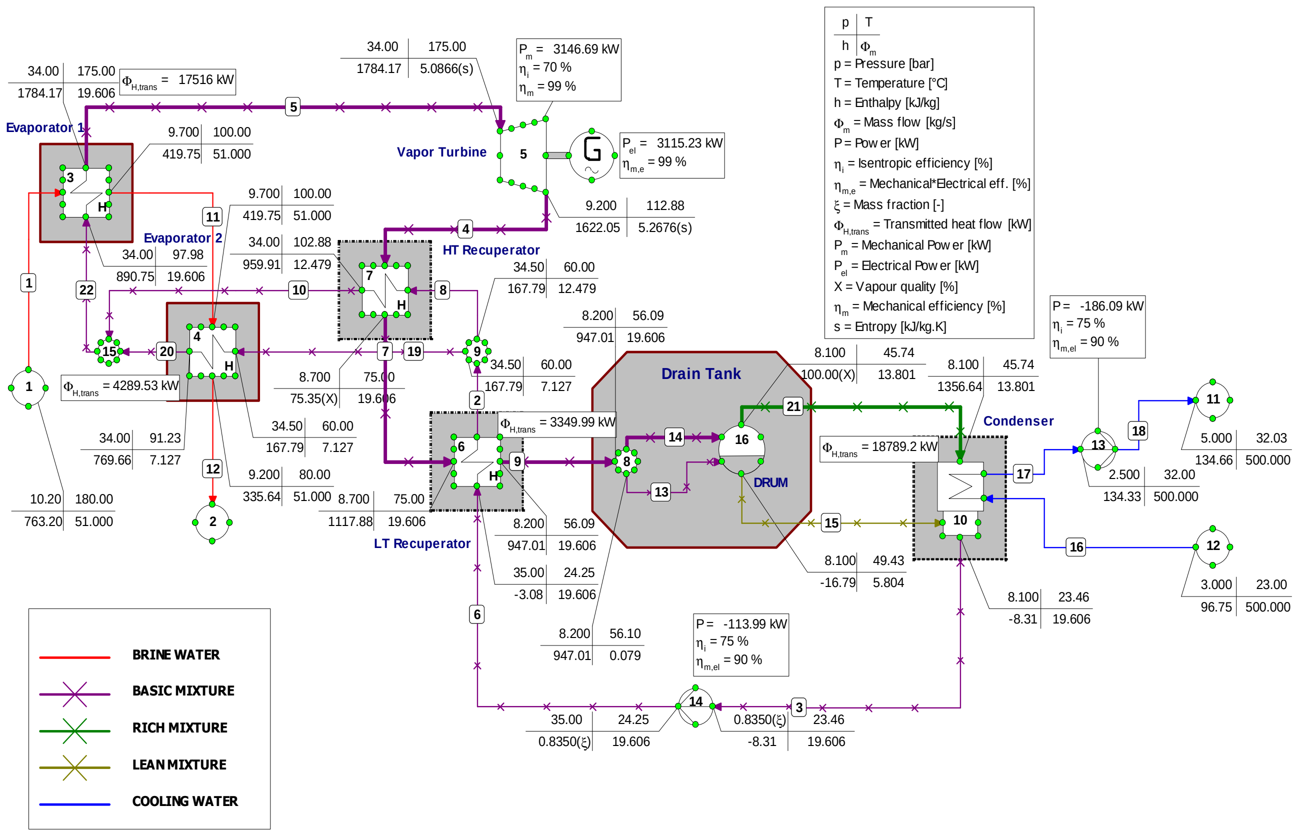

Figure 6. KCS 11 Optimum Condition (using Cycle Tempo Simulation) [4]

Table 3. State Properties of the Stream of KCS 11 for the Optimal Condition

Flows	Temperature (°C)	Pressure (bar)	Mass flow (kg s^{-1})	NH3 Concentration (%)	Physical Exergy (kW)	Chemical Exergy (kW)	Total Exergy (kW)
1	180	10.2	2.83	0	6179.86	0	6179.86
2	60	34.5	19.6	83.5	4333.91	324440	328773.88
3	23.46	8.1	19.6	83.5	4131.35	324440	328571.32
4	112.88	9.2	19.6	83.5	6639.67	325983.5	332623.15
5	175	34	19.6	83.5	10893.96	325983.5	336877.44
6	24.25	35	19.6	83.5	4206.76	324440	328646.73
7	75	8.7	19.6	83.5	4744.48	325983.5	330727.96
8	60	34.5	12.48	83.5	2758.45	206582.2	209340.63
9	56	8.2	19.6	83.5	4277.64	325983.5	330261.12
10	102.88	34	12.48	83.5	4276.36	207565	211841.35
11	100	9.7	51	0	1545.68	0	1545.68
12	80	9.2	51	0	835.58	0	835.58
13	56	8.2	0.079	83.5	26	1313.913	1339.913
14	56	8.2	19.527	83.5	4258.83	324769.4	329028.19
15	49.4	8.1	5.8	54	297.61	62093.96	62391.574
16	23	3	500	0	271.37	0	271.37
17	32	2.5	500	0	88.39	0	88.39
18	32.03	5	500	0	214.27	0	214.27
19	60	34.5	7.127	83.5	1575.46	117973.7	119549.12
20	91.23	34	7.127	83.5	2198.17	117973.7	120171.83
21	45.74	8.1	13.8	99.6	4107.23	272496.9	276604.16
22	97.98	34	19.6	83.5	6465.21	325983.5	332448.69

4. Conclusions

The following conclusions can be presented based on the result of simulation and analysis: 1) For the specific Lahendong geothermal site conditions (brine water, climate, cooling water source, etc.), the Kalina cycle KCS 11 system will yield the optimum operating conditions at 83.5% ammonia mass fraction in the ammonia-water mixture and 9.2 bar turbine exhaust pressure. This optimum operating conditions will produce 3115 kW gross electrical power, having 83.5% gross exergy efficiency, and total turbine exergy losses of 1107 kW; 2) For a specific ammonia mass fraction value in consideration, the highest exergy efficiency will be obtained at the lowest possible turbine exhaust pressure; 3) The lower the ammonia mass fraction in the working fluid, the higher the power output that can be obtained in the turbine generator; 4) The most optimum thermodynamic cycle tends to be obtained at low ammonia mass fraction and low turbine exhaust pressure. However, one can not lower these two parameters as low as imaginably possible, because the selection of these two parameters in dependent on site specific conditions, such as climate, available cooling water temperature, and cooling water temperature rise permitted by the environmental regulations; 5) The biggest irreversibilities causing the biggest exergy loss occurred in the Turbine. This phenomenon makes optimization in the turbine more critical than in other apparatuses. For planning a new KCS-11 power station, it is necessary to select the most efficient turbine in order to maximize the overall exergy efficiency of the system.

References

[1] H.A. Mlcak, European Geothermal Energy Council, 2nd Business Seminar EGEC, 2001.
[2] A. Bejan, G. Tsatsaronis, M. Moran, Thermal Design and Optimization, John Wiley & Sons, New York, 1996, p.542.
[3] J. Ahrendts, Energy Int. J. 5 (1980) 667.
[4] Cycle-Tempo R.5, Delft University of Technology (TU Delft), 2006.