Energy and exergy analysis of kalina cycle system (KCS) 34 with mass fraction ammonia-water mixture variation[†]

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Abstract

Further utilization of waste heat produced by power plant system will increase the efficiency of the whole power plant system. The Kalina Cycle offers alternative solution to generate additional power from waste heat or from low temperature geothermal resources. The modeling application on energy system is used to study the basic design of thermal system, which uses Kalina Cycle for further utilization of geothermal brine water. If this geothermal brine water were not used in the Kalina Cycle, it would be reinjected to the geothermal reservoir and its remaining energy content would have been wasted. The study of this process is done by *Cycle Tempo 5.0* simulation software, to obtain the data of efficiency, energy and exergy that could be generated from the heat source. An ammonia-water mixture is used as a working fluid on Kalina cycle system (KCS) 34. In order to obtain the maximum power output and maximum efficiency, the system will be optimized on the mass fraction of working fluid and also on the turbine output pressure. The result of the study shows that the maximum efficiency and power output are achieved at 78% ammonia-water mixture.

Keywords: Ammonia-water; Exergy; Kalina cycle; Power plant

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1. Introduction

In order to reduce primary energy consumption in the energy systems, to conserve energy and to reduce environmental pollution, new thermodynamic cycles have been investigated and developed during the past 20 years.

Kalina cycle system (KCS) 34 was invented by Dr. Alexander Kalina specifically for generating electricity using low to medium temperature geothermal resources as a "topping" thermodynamic cycle prior to district heating. A flow diagram of Kalina cycle system (KCS) 34 is shown in Fig. 1. The basic flow parameters are shown on this diagram.

This research is made for studying, modeling and analysis of a Kalina cycle system (KCS) 34 system that has been applied in Husavic, Iceland. The final conclusion is validation model and selection of working fluid composition that have improved efficiency of thermal power production.

In this study, the efficiency, energy and exergy that could be generated from heat source will be analysed. An ammonia-water mixture is used as a working fluid on Kalina cycle system (KCS) 34. In order to obtain the maximum power output and maximum efficiency, the system will be optimized on the mass fraction of working fluid and also on the turbine output pressure. The possibility of using Kalina cycle system (KCS) 34 in Indonesia was also be analysed where some parameters are different from the Iceland conditions.

2. Methods

2.1 Cycle description

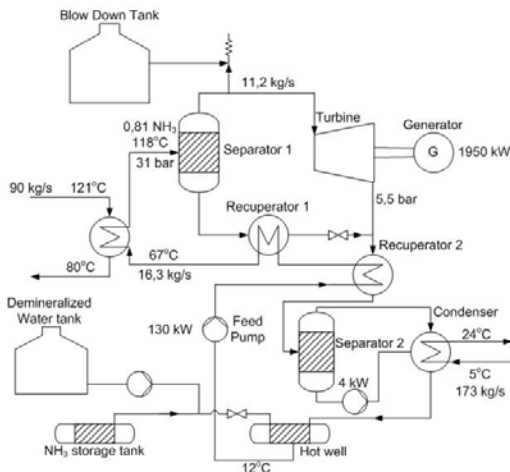Fig. 1 shows the schematic diagram of Kalina cycle

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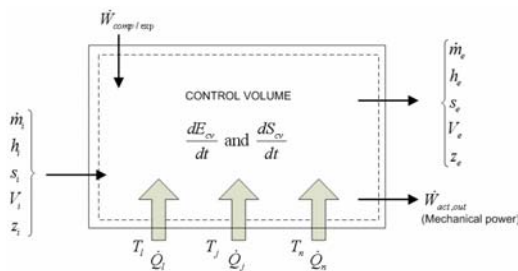Fig. 1. Flow diagram - orkuveita húsavíkur geothermal power plant [1].

Fig. 2. A control volume which exchanges energy by heat transfer Q, at surface temperature T_j [2].

system (KCS) 34 for geothermal power plant [1] which be used in this study. The hot water or brine water enters the evaporator and the heat is transferred to ammonia-water and the ammonia water goes into turbine and the turbine generates the electricity.

2.2 Exergy analysis method

The thermomechanical exergy associated with the state of a system is measured by the maximum reversible work that could be delivered by the system as it proceeds toward a state of equilibrium with the environment while any heat transfer occurs solely with the environment. This state of equilibrium is its dead state at T_0 and P_0, and the standard atmosphere or environment which be used in this study are 298.15 K and 1.01325 bar (1 atm).

Fig. 2 shows the energy and entropy balances in a control volume which exchanges energy by heat transfer $\dot{Q}$ at surface temperature T_j. The rate of net useful work $\dot{W}_{act,u}$ in a control volume at steady state

is defined with the following equation

$$
\begin{aligned}
\dot{W}_{act,u} = & \sum_{out} \left(h + \frac{V^2}{2} + gz - T_0 s \right)_e \cdot \dot{m}_e \\
& - \sum_{in} \left(h + \frac{V^2}{2} + gz - T_0 s \right)_i \cdot \dot{m}_i \\
& - \sum_{j=1}^{n} \dot{Q}_j \left(1 - \frac{T_0}{T_j} \right) + T_0 \dot{\sigma}_{cv}
\end{aligned}
\tag{1}
$$

The summation terms for the inlets and exits can be replaced by the stream exergy function. The next-to-last term is the exergy transfer associated with the heat transfer $\dot{\Phi}_Q$, and the last term $T_0 \dot{\sigma}_{cv}$ measures the irreversibility within the control volume $\dot{I}_{CV}$. As a result, the net rate of transfer of exergy out of a control volume can be written in the following form :

$$
\sum_{out} \dot{E}_e - \sum_{in} \dot{E}_i = \dot{\Phi}_Q + \dot{W}_{act} - \dot{I}_{CV}
\tag{2}
$$

The total exergy of the system becomes the summation of physical exergy and chemical exergy

$$
\dot{E} = \dot{E}_{ph} + \dot{E}_{ch}
\tag{3}
$$

The physical exergy component $\dot{E}_{ph}$ is calculated using the following relation:

$$
\dot{E}_{ph} = m \left[(h - h_0) - T_0 (s - s_0) \right]
\tag{4}
$$

The calculation procedure for the chemical exergy of various substances based on the standard chemical exergy values of respective species is widely discussed. For the ammonia-water fluids to be considered, the chemical exergy of the flow is calculated using the following relation:

$$
E_{ch} = m \left[\left(\frac{x}{M_{NH_3}} \right) e_{ch,NH_3}^0 + \left(\frac{1-x}{M_{H_2O}} \right) e_{ch,H_2O}^0 \right]
\tag{5}
$$

where e_{ch,NH_3}^o and e_{ch,H_2O}^o are the standard chemical exergy of ammonia and water, respectively, and their values are taken from Ahrendts [3].

First and second-law efficiencies are different in one other important respect. The first law is a conservation principle. On the other hand, entropy and exergy from a second-law viewpoint are non conserved properties. In the presence of irreversibilities, entropy is produced and exergy is destroyed. Hence second-law effi-

ciencies measure losses in exergy during a process. A general definition of a second-law effectiveness is

$$\varepsilon = \frac{\text{useful exergy out}}{\text{exergy in}}$$
$$= 1 - \frac{\text{exergy destruction and losses}}{\text{exergy input}} \quad (6)$$

Gross thermal efficiency =
$$\frac{\text{Total produced electric / mechanical power}}{\text{Total energy input}} \quad (7)$$

Total produced electric/mechanical power is $P_{generator}$ or power from generator, meanwhile the total own consumption is amount of energy use to run the plant auxiliaries, such as the pump or total P_{pump} and the total energy input is total heat absorbed to evaporator.

The net exergy efficiency is calculated by the following equation:

$$\eta_{II} = \frac{\text{Exergy out - (aux. power)}}{\text{Exergy absorb}} \times 100\% \quad (8)$$

2.3 Simulation and description

The schematic model of Kalina cycle system (KCS) 34 is built using Cycle-Tempo 5.0 [4] as shown in Fig. 3. For the input data were the actual data from Húsavík power plant. The hot brine as heat source is supplied through evaporator as a boiler transferring the heat to ammonia-water (1 and 2) and cooling water flow as heat sink is shown at 9 and 11. The input and parameter were made similar to the condition in Húsavík [5] .

2.4 Optimization

The optimum point of the system which indicated by the maximum power output of the turbine can be done with the two-step following procedures. First, we have to find the plausible range of ammonia-water

mass fraction in the system without violation of the mass and energy balances. Based on the running simulation, we can find that the plausible value of the ammonia-water mass fraction, for Kalina cycle system (KCS) 34 in Indonesian conditions the value is between 78% and 85.5% of Ammonia mass fraction. But this range is not yet already optimized. The next step is to find the optimum turbine outlet pressure in order to get maximum power output in this mass fraction range. The ammonia-water mass fraction and turbine output must be in the range values mentioned in Table 2 due to the constraints in Indonesian environmental conditions. The optimization metho-dology is a searching method, which verified using Cycle Tempo 5.0.

The selection of lower limit and upper limit of ammonia-water mass fraction and turbine output are constrained by specific environmental conditions in typical Indonesian geothermal sites, such as: ambient temperature (18-24°C), available cooling water temperature, usually from the nearby river (20-24°C), relative humidity (70-95%), in order to produce the highest possible electrical output. These input conditions for our simulation are different with Iceland conditions. Furthermore the selection of ammonia-water fractions are also constrained by the specific thermodynamic properties of ammonia-water mixture as can be seen in the following T-X diagram.

3. Results and discussion

3.1 Model validation

The simulation results at the steady state condition will be compared to the real operation data of Kalina cycle geothermal power plant in Husavic, Iceland.
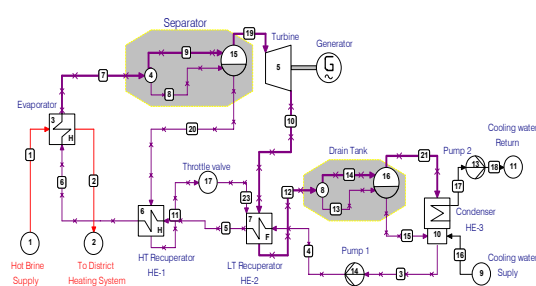

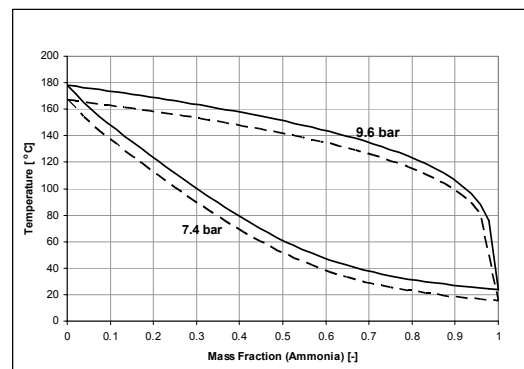Fig. 3. Kalina cycle system (KCS) 34 scheme model.

Fig. 4. T-x Diagram at optimum pressure range [6].

Table 1. Results comparisons.

Apparatus	Parameter	KCS 34 (real)	KCS 34 (simulated)
Pump 1	Pout Tout Power consumption	35 bar 13°C 130 kW	35 bar 12.9°C 100.59 kW
HT Rec.	Tout 1	67°C	67°C
Evaporator	Pout 1 Tin 2 Tout 2 Tout 1	31 bar 121°C 80°C 118°C	31 bar 121°C 80°C 118°C
(*Brine Water*)	$\dot{m}$ supply	90 kg/s	90 kg/s
Separator 1	$\dot{m}$ ammonia-water to turbine Mass fraction to turbine	11.2 kg/s $\pm$95%	12.37 kg/s 96.2%
Turbine	Tin Tout Pout	$\pm$120°C 53 – 60°C $\pm$5.5	118.2°C 52.21°C 5.5 bar
Condenser (cooling water)	$\dot{m}$ cooling water Tin 1 Tout 2	173 kg/s 5°C 24°C	173 kg/s 5°C 24°C
Generator	Gross electric power	1,950 MW	1.959 MW

Table 1 shows that using the same input parameters, the results of the simulation are very close with the actual site data, except the power consumption for the feed pump which has the value lower than the real condition. It can be explain that the assumed parameters for this feed pump are different from the real condition. Generally, it can be concluded that the scheme and all input for each apparatus could be used for further analysis.

The exergy flow of the above Kalina cycle is shown in Grassman Diagram as shown in Fig. 5. The dashed box refers to a component of the system.

The above Grassman diagram shows the exergy flow in the KCS 34 at the optimum condition. Apparatus denoted in number. I=Evaporator, II=separator, III=turbine, IV=generator, V=LT Recuperator, VI=drain tank, VII=condenser, VIII= pump, IX= HT recuperator, all the unit is in kW. The losses in heat exchanging equipment such as apparatus number I, II, V, VII and IX are caused by pressure drop and heat transfer occurred. Turbine has the highest losses is caused by mechanical and isentropic efficiency.

In order to obtain the optimum performance of the system, the Kalina cycle should be optimized using the
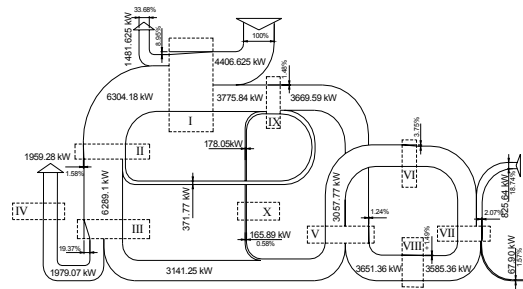

Fig. 5. Grassman diagram of exergy flow in KCS 34.

criteria of the highest achievable thermal as well as exergy efficiencies of the system which can be indicated with the maximum power produced in turbine, by varying the feasible ammonia-water mass fraction and turbine exit pressure as the most influential parameters. Table 3 shows that the increasing of the thermal efficiency (1st Law) will be followed by the increasing of the 2nd law efficiency.

3.2 KCS 34 application in Indonesia

Geothermal site in Iceland has different environment and climatic conditions with Indonesia. In Indonesia, geothermal resources in normally located in the mountainous area, several hundred or thousands meters above sea level. However, the climatic condition in Indonesia is not as cold as Iceland. Typical air temperature at Indonesian Geothermal Site is around 18-24°C. The cooling water source is normally taken from nearby river, with river water having average temperature between 20-24°C. Meanwhile the cooling water supply temperature in Iceland is about 5°C. Hence, some thermodynamic parameters should be changed in order to obtain the maximum electric power and efficiency using Kalina cycle system (KCS) 34 for Indonesian conditions.

Kalina cycle system (KCS) 34 system parameters in the simulation model are then adjusted to find the optimum power output. To obtain the optimum power output, ammonia-water composition is considered as the most influenced parameters, so it will be varied starting from 78% up to 85.5% mass fraction, and each mass fraction acts as a constraint, which affects the outlet pressure from turbine (lower and upper limit). The results are shown in Table 2.

Fig. 6 shows that the highest electric power produced can be achieved at 78% ammonia-water mass fraction and 7.4 bar outlet pressure, which can produce around 2.145 MW. Refer to Fig. 6 and Table 3, by

Table 2. Optimum pressure range.

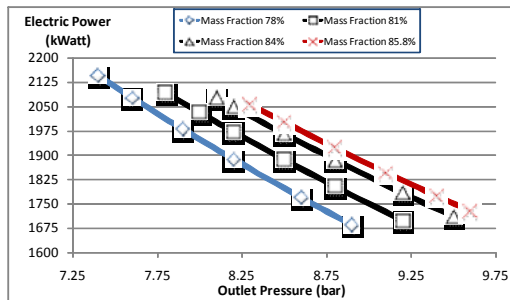| Mass fraction	Turbine output pressure
(%) ammonia	(bar)
78	7.4 - 8.9
81	7.8 - 9.2
84	8.1 - 9.5
85.5	8.3 - 9.6

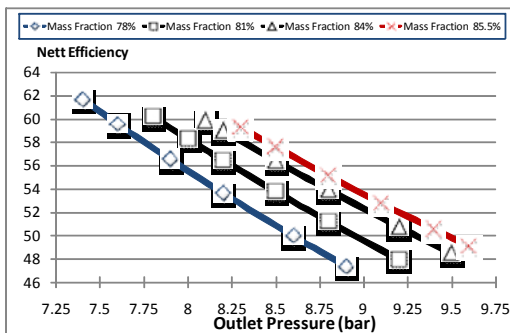Fig. 6. Power output of the system as function of mass fraction and turbine outlet pressure.

Fig. 7. Exergy efficiency as function of mass fraction and turbine outlet pressure.

increasing the electric power output and lowering the outlet pressure, the efficiency will increase as well as the exergy efficiency.

For each mass fraction, Fig. 7 shows that the increasing of the outlet pressure from turbine will decrease the exergy efficiency, because of the exergy absorbed by the system from heat source is constant meanwhile the outlet pressure will increase leads to decreasing electrical power as useful work.

For mass fraction 85.5% the highest exergy efficiency is $\eta_{II} = 69\%$, mass fraction 84% is 68.6%, mass fraction 81% is 67.1%, mass fraction 78% is 66.9%, and in a series the pressure are 8.3 bar ; 8.1 bar ; 7.8 bar ; and 7.4 bar, those are bottom line each mass fraction respectively.

Table 3. Energy and exergy efficiency.

Mass fraction	Efficiency			
	Energy net (%)	Energy net (%)	Exergy net (%)	Exergy net (%)
	Lowest	Highest	lowest	Highest
78	8.64	11.24	51.41	66.88
81	8.75	10.97	53.45	67.06
84	8.84	10.91	55.63	68.62
85.5	8.95	10.81	57.15	69.00

This analysis refers to the study of Kalina cycle system (KCS) 34 application in Indonesia, the important things are how to choose the mass fraction and outlet pressure from turbine that maximize electric power output and also system efficiency.

4. Conclusions

Kalina cycle system (KCS) 34 simulation model using Cycle Tempo 5.0 has been established to validate a model for real installation in Husavic, Iceland. The model has produced calculated electrical output of 1.959 MW, which is close to real condition in Husavic site which currently produces electrical power output of 1.950 MW.

It is concluded that if the outlet pressure from turbine is constant, by increasing the ammonia mass fraction the electrical power output will increase and so does the system efficiency. If the mass fraction is constant, by decreasing exit pressure from turbine, it will increase the electrical power output and the system efficiency.

The highest electrical power output for Kalina cycle system (KCS) 34, if it were applied in Indonesia, could be achievable using 78% mass fraction of ammonia-water and 7.4 bar exit pressure from turbine.

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