Modeling and analysis of Low Temperature Kalina Cycle System

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ABSTRACT

Kalina Cycle is a proven thermodynamic cycle. It improves the efficiency of conventional Rankine cycle at low source temperatures.Ammonia-water binary mixture is used as working substance in the Kalina cycle systems. The efficiency of Kalina cycle system depends mainly on the ammonia mass fraction in basic solution besides separator parameters and material flow arrangements through the system components. A new configuration of low temperature Kalina cycle system is designed with an effort to increase the cycle efficiency. The ammonia concentration of the vapor mixture in the separator is enhanced by incorporating an auxiliary separator. Heat load in the heat recovery steam generator is reduced by modifying the flow of working fluid in the system. Parametric analysis of the system has been carried out and the operating parameters of the system have been optimized. A maximum cycle efficiency of 13.06% is resulted for an optimum ammonia mass fraction of 0.5 in the basic solution operating at 128ºC. The results of analysis are presented in the form of charts and are useful for determining optimum operating parameters of low temperature Kalina cycle system operating at temperatures up to 140ºC.

KEY WORDS: Ammonia mass fraction, Kalina Cycle, Low temperature heat source, Thermodynamic analysis.

1. INTRODUCTION

As the non-renewable energy resources of the world are getting depleted, researchers are focusing on new technologies for harnessing renewable energy resources besides developing more efficient energy conversion systems. The efficiency of steam power plants operating on conventional Rankine cycle is limited due to isothermal boiling nature of the water as well. Kalina cycle is a well-known cycle that uses ammonia-water mixture as working substance and capable of generating electricity form low temperature heat sources more efficiently. The gain in efficiency over Rankine cycle particularly in low temperature range makes it ideal for power generating application. The heat from the geothermal brine, gas turbine exhaust, Industrial waste heat etc. may be utilized to generate electricity using Kalina cycle systems. The simulation and optimization of ammonia-water mixture based power generating systems require simple and efficient functional forms to evaluate the thermodynamic properties of ammonia-water mixture at various state points in the cycle. Equations for evaluating the thermodynamic properties of ammonia-water mixture using Gibbs free energy are described. The data on properties of ammonia-water mixture is reviewed and extended up to 316°C. A general code is developed for evaluating thermodynamic properties of ammonia-water mixture using Peng-Robinson equation. A set of five equations depicted to determine the vapour-liquid equilibrium properties of ammonia-water mixture avoiding iteration. The advantage of Kalina cycle over steam bottoming cycle and heat recovery from the gas turbine exhaust with Kalina bottoming cycle is presented. The feasibility of vapor generation and absorption condensation process is verified experimentally. Kalina cycle may be designed as an independent cycle to utilize low temperature heat sources such as geothermal and solar or as a bottoming cycle to utilize waste heat from the conventional power cycle. The analysis of the cycle and the performance characteristics of a low temperature Kalina power plant using solar energy are illustrated. The assessment of series and parallel arrangement of heat exchangers in Kalina cycle station is made. In the present work, a new configuration of Kalina cycle system for generating power by utilizing low temperature heat source is designed. Efforts have been made to increase the thermal efficiency of the cycle by reducing thermal load in the heat recovery vapor generator. The effect of key parameters on the cycle performance has been investigated and the optimum operating parameters have been determined for maximum efficiency.

2. METHODOLOGY

Kalina cycle is optimized based on maximum efficiency. The efficiency of low temperature Kalina cycle system increases with ammonia mass fraction in the vapor mixture. In order to enhance the ammonia mass fraction in vapor mixture, an auxiliary separator is incorporated in the system. The heat load in heat recovery steam generator is reduced by decreasing the mass flow rate through it. The stream of high pressure strong solution is passed in parallel through high temperature heat exchanger and the heat recovery steam generator. The thermodynamic properties of ammonia-water mixture are computed using combined Gibbs free energy method. A computer program has been coded to determine the properties of ammonia-water mixture at different state points and to compute efficiency of the cycle for the given operating parameters. The performance of the ammonia-water based power plant is predominantly influenced by separator pressure, temperature and ammonia mass fraction and hence these parameters are considered for thermodynamic analysis.

The feasible ranges of operating parameters have been determined for the assumed source temperature. The ammonia mass fraction in basic solution is optimized by fixing the ammonia mass fraction in vapor mixture whereas the ammonia mass fraction in vapor mixture is optimized by fixing the ammonia mass fraction in basic solution.

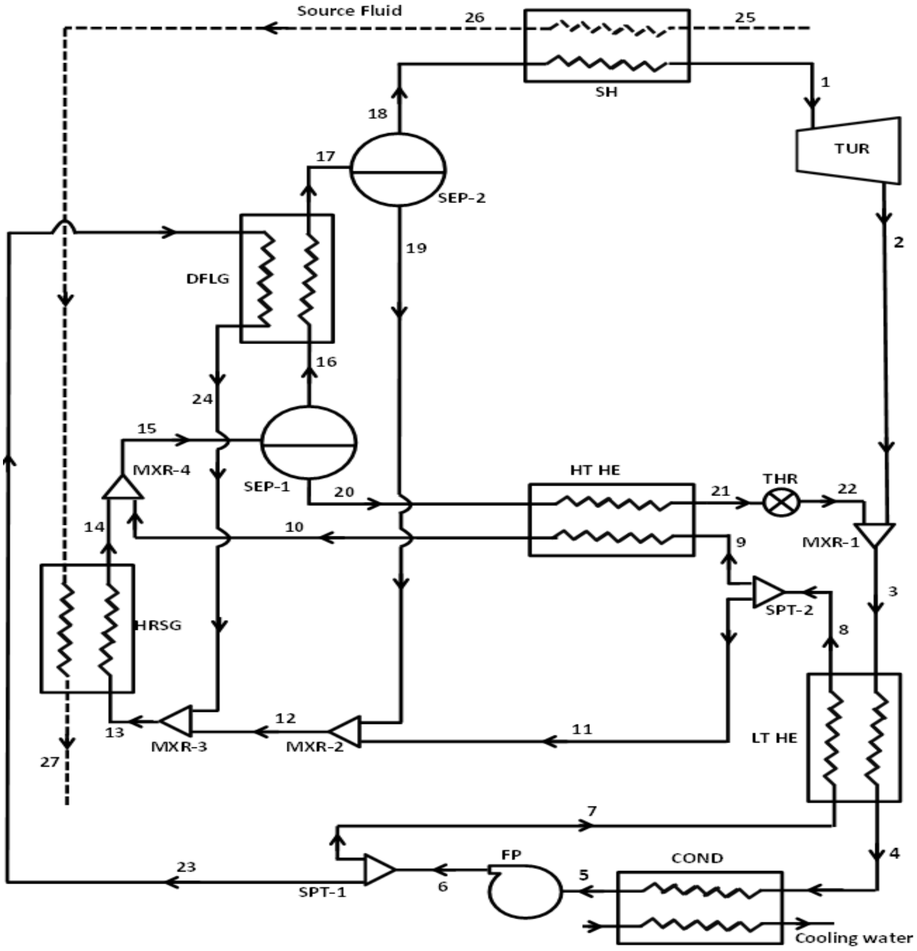

Figure.1. Schematic of Low Temperature Kalina Cycle System

(HRSG: heat recovery steam generator; MXR: mixer; SEP: separator; DFLG: deflegmator; SH: superheater; TUR: turbine; THR: throttle valve; SPT: splitter; HT: high temperature; LT: low temperature; HE: heat exchanger; COND: condenser; FP feed pump)

System modelling and description: The schematic diagram of low temperature Kalina cycle system with an auxiliary separator and parallel flow arrangement through heat exchangers is depicted in the Figure 1. Ammonia-water mixture is used as working fluid in the system. The heat from the source fluid is recovered in the heat recovery steam generator. The high pressure working fluid branching out through the low temperature heat exchanger at state point 8 is passed simultaneously through the high temperature heat exchanger and heat recovery steam generator. The working fluid at state point 15 is separated into liquid and vapor mixture. The vapor mixture from state point 16 is passed through an auxiliary separator to enhance the ammonia mass fraction in the vapor mixture at state point 18. It is than heated in the super heater to state point 1.The high pressure vapor mixture at state point 1 is expanded in the turbine to generate electricity. The turbine exit fluid rejects heat in the low temperature heat exchanger. The high pressure liquid mixture at state point 20 from the separator is throttled to low pressure after rejecting heat in the high temperature heat exchanger. The turbine exit fluid at state point 2 is mixed with the ammonia-weak solution at state point 22 in the mixer to state point 3. It is then condensed to saturated liquid in the condenser to state point 5. The condensate passing through the pump at state point 6 is divided into two streams. Whereas the stream at state point 7 is passed through the low temperature heat exchanger, the other stream at state point 23 is passed through the deflegmator. The stream at state point 8 is divided into two streams. One of the streams at state point 9 is passed through high temperature heat exchanger whereas the other at state point 11 is mixed with the lean mixture at state point 12, originating from the auxiliary separator at state point 19. The two streams at state points 10 and 14 are mixed to state point 15 and passed through the separator to repeat the cycle.

Thermodynamic analysis: The thermodynamic analysis of the Kalina cycle system has been done to verify the feasibility of producing electricity from low temperature heat sources ranging from 100ºC to 165ºC. Table 1 shows the operating conditions of the Kalina cycle system assumed during the analysis. The separator and condenser pressure is determined from the temperature and concentration of the working fluid as it is the function of temperature and ammonia concentration at saturated state. The turbine exit temperature is determined by entropy equalization for isentropic expansion of the vapor mixture.

Table.1. Kalina Cycle System Operating Conditions

Parameter	Value
Ambient Temperature	25ºC
Terminal Temperature Difference	10ºC
Pinch Point in Steam Generator and Condenser	5ºC
Degree of Superheat	50ºC
Isentropic Efficiency	75%
Efficiency of Turbine	96%
Efficiency of Electric Generator	98%

The temperature of the liquid mixture at the state point 20 will be equal to the bubble point temperature and therefore the ammonia mass fraction of liquid mixture is evaluated through iteration. Pressure drop and heat loss in pipe lines are neglected. The condensate leaving the condenser is saturated liquid.The condenser pressure is determined from ammonia mass fraction and condenser temperature. The unknown properties i.e. temperature, concentration and mass flow rates at various state points are determined by mass, concentration and energy balance equations.

The mass of vapor leaving the separator at state point 16, $m_{16} = \frac{(x_{15} - x_{20})}{(x_{16} - x_{20})}$ (1)

The mass of vapor leaving the separator at state point 18

Table.2. Material Flow Details of Kalina Cycle System depicted in Figure 1 at 125ºC Separator Temperature

State Point	Temperature ºC	Pressure bar	Ammonia Mass Fraction	Flow Rate kg/sec	Specific Enthalpy kJ/kg
1	143.50	24.00	0.98	0.19	1579.15
2	34.30	3.70	0.98	0.19	1321.68
3	30.89	3.70	0.50	0.97	327.36
4	30.89	3.70	0.50	0.97	186.38
5	30.00	3.70	0.50	0.97	-110.65
6	30.24	24.00	0.50	0.97	-107.85
7	30.24	24.00	0.50	0.85	-107.85
8	65.18	24.00	0.50	0.85	52.84
9	65.18	24.00	0.50	0.40	52.84
10	120.00	24.00	0.50	0.40	561.61
11	65.18	24.00	0.50	0.45	52.84
12	67.10	24.00	0.50	0.48	61.74
13	84.70	24.00	0.50	0.60	144.46
14	128.34	24.00	0.50	0.60	694.22
15	125.00	24.00	0.50	1.00	641.68
16	125.00	24.00	0.92	0.22	1587.36
17	93.50	24.00	0.92	0.22	1265.74
18	93.50	24.00	0.98	0.19	1435.27
19	93.50	24.00	0.55	0.03	193.23
20	125.00	24.00	0.38	0.78	346.87
21	70.18	24.00	0.38	0.78	89.10
22	70.68	3.70	0.38	0.78	89.20
23	30.24	24.00	0.50	0.12	-107.85
24	115.00	24.00	0.50	0.12	481.62

$$m_{18} = \left(\frac{x_{17} - x_{19}}{x_{18} - x_{19}}\right) m_{17} \quad (2)$$

Work output of the turbine, $W_t = m_1 (h_1 - h_2) \eta_t \eta_g$ (3)

The work input to the pump, $W_p = \frac{m_5 (h_6 - h_5)}{\eta_p}$ (4)

Net output of the cycle, $W_{net} = (W_t - W_p)$ (5)

Heat supplied in heat recovery steam generator, $Q = m_{13}(h_{15} - h_{13}) + m_{18}(h_1 - h_{18})$ (6)

Efficiency of the Kalina cycle, $\eta_{cycle} = \frac{W_{net}}{Q}$ (7)

Heat load in low temperature heat exchanger = $m_7(h_8 - h_7)$ (8)

Heat load in high temperature heat exchanger = $m_{17}(h_{17} - h_{18})$ (9)

3. RESULTS AND DISCUSSION

The performance of Kalina cycle system is thermodynamically investigated for the specified operating conditions. Table 2 shows the material flow details of the Kalina cycle system described in Figure 1. Table 3 contains the specifications of low temperature Kalina cycle system established for unit mass of the working fluid and 125°C separator temperature. The influences of separator temperature, ammonia mass fraction in basic solution and turbine inlet vapor mixture have been examined for cycle efficiency and specific power. The results are presented in the following sections.

Table.3. Specifications of Kalina Cycle System at 125°C Separator Temperature

Description	Value
Separator temperature, °C	125
Ammonia mass fraction in basic solution	0.5
Ammonia mass fraction in vapor mixture	0.98
Work output of turbine, KW	46.31
Electricity output, kW	42.54
Heat load in condenser, kW	287.91
Heat load in heat recovery vapor generator, kW	327.17
Heat load in low temperature heat exchanger, kW	136.64
Heat load in high temperature heat exchanger, kW	70.12
Specific Power, kW/kg/s	42.54
Kalina cycle energy efficiency, %	13.00

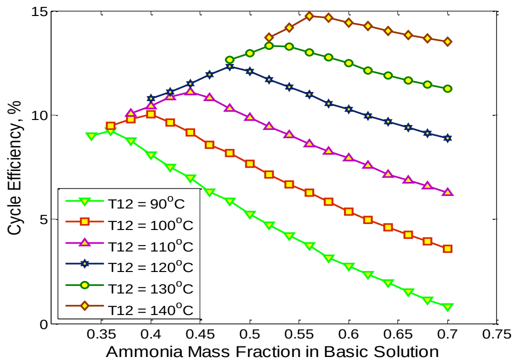

Figure.2. Variation of Cycle Efficiency with Ammonia Mass Fraction in Basic Solution

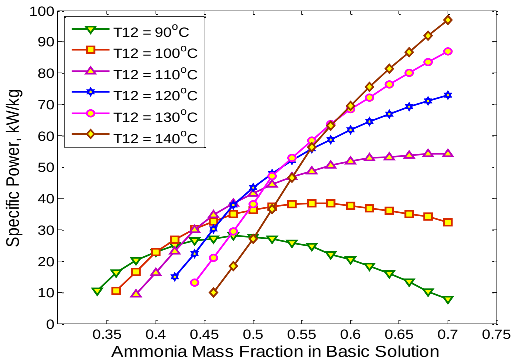

Figure.3. Variation of Specific Power with Ammonia Mass Fraction in Basic Solution

Influence of Ammonia Mass Fraction in Basic Solution on Cycle Efficiency: The variation of cycle efficiency with ammonia content in basic solution is depicted in Figure 2. The results are plotted for six different separator temperatures ranging from 90°C to140°C. It has been observed that the efficiency rises with the ammonia mass fraction, reaches a maximum value and decreases further. For every separator temperature the maximum efficiency occurs at an optimum value of ammonia mass fraction. Further the efficiency is observed to be higher for higher separator temperature values. For separator temperature of 140°C, the maximum efficiency is observed at 0.6 ammonia mass fraction in the basic solution.

Influence of Ammonia Mass Fraction in Basic Solution on specific Power: Figure 3 depicts the effect of ammonia mass fraction in basic solution on specific power for fixed separator temperatures**.** The ammonia mass fraction is varied in the feasible range from 0.35 to 0.7. It has been observed that the specific power rises with the ammonia mass fraction, reaches a peak value and decreases thereafter. For each separator temperature the maximum specific power will be obtained at an optimum value of ammonia mass fraction in the basic solution.Similar to cycle efficiency, the specific power is observed to be higher for higher separator temperature. Referring to 140°C plot in the figure, the maximum specific power is observed at 0.7ammonia mass fraction in the basic solution. It is to be noted that the optimum mass fraction for maximum efficiency and maximum specific power are different.

Influence of Ammonia Mass Fraction in Vapor Mixture on Cycle Efficiency: The variation of cycle efficiency with ammonia mass fraction in vapor mixture is depicted in Figure 4. The efficiency curves are plotted for four different separator temperatures. It is understood that the cycle efficiency increases with the ammonia mass fraction in vapor mixture. Also the efficiencies are observed to be higher for higher separator temperature values. A maximum of 13.0% cycle efficiency is resulted with 0.98 ammonia concentration in the vapor mixture operating at 125°C separator temperature.

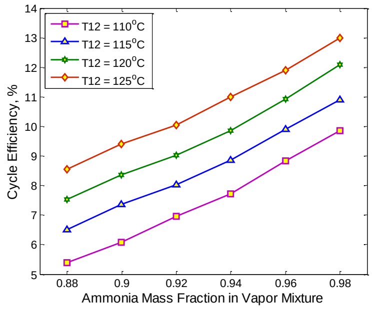

Figure.4. Variation of Cycle Efficiency with Ammonia Mass Fraction in Vapor Mixture

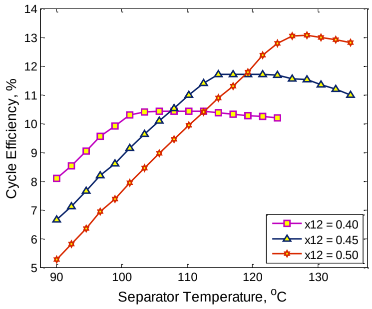

Figure.5. Variation of Cycle Efficiency with Separator Temperature

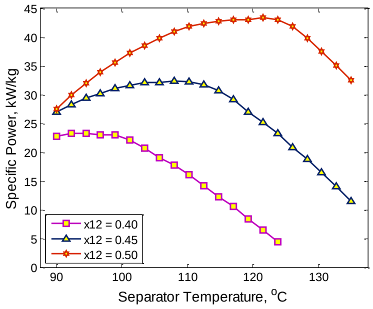

Figure.6. Variation of Cycle Efficiency with Separator Temperature

Influence of Separator Temperature on Cycle Efficiency: Figure 5 illustrates the influence of separator temperature on cycle efficiency. The efficiency curves are plotted for three fixed ammonia concentration values in the basic solution. The separator temperature is varied from 90°C to 135°C. The cycle efficiency increases with separator temperature till the peak value is reached and then decreases. It is observed that the optimum values of separator temperatures for maximum efficiency increases with the ammonia concentration in basic solution.

Influence of Separator Temperature on Specific Power: The variation of specific power with separator temperature is depicted in Figure 6 for three different ammonia concentration values in basic solution. The separator temperature is varied from 90°C to 135°C. The specific power increases with separator temperature. Similar to efficiency, the maximum specific power results at an optimum value of separator temperature. It is noted that the optimum separator temperature for maximum efficiency and maximum specific power are different.

CONCLUSION

Kalina cycle system has been modelled and analysed successfully to demonstrate the feasibility of utilizing the low temperature heat sources. It has been modelled thermodynamically and analyzed parametrically. The cycle efficiency and specific power are evaluated and the variation tendency is analyzed. It emerges that, for a given separator temperature, there exist an optimum value of ammonia mass fraction in the basic solution that yields maximum efficiency and power output. The cycle efficiency increases with an increase in separator temperature and also corresponding to the much richer ammonia-water mixture at the turbine inlet. The potential for obtaining work from the low temperature heat sources was evidenced. The new configuration of the Kalina cycle system is found to be feasible. The ammonia mass fraction in the vapor mixture at the turbine inlet can be enhanced by incorporating an auxiliary separator. The sharing of the heat load between heat recovery steam generator and high temperature heat exchanger improves the performance of the system under given operating conditions. Improvement in the system design to reduce losses, more particularly the boiling process prepares the system for next phase of testing.

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