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THERMODYNAMIC MODELLING AND ANALYSIS OF LOW TEMPERATURE KALINA CYCLE SYSTEM FOR GEOTHERMAL SOURCES OF INDIA

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ABSTRACT

The India is having good potential for geothermal energy and is yet to be explored. The non-isothermal boiling nature of ammonia-water mixture paved the way for the development of Kalina cycle systems. In this work the low temperature Kalina cycle system is investigated with the aim of generating electric power from the geothermal resource at Indian climatic conditions. The study of the process is done using computer software to obtain the data of energy and exergy efficiency that could be generated form the geothermal heat source. Parametric analysis is conducted to examine the effects of some key thermodynamic parameters on the system performance. One of these parameters, ammonia concentration at turbine inlet, appears to have an optimum value with respect to the maximum cycle efficiency and net power output at the given operating conditions. Results indicate that a maximum cycle efficiency of 11.75 % can be achieved with 0.95 and 0.70 ammonia concentration at the turbine inlet and separator inlet respectively, operating at 418 K source temperature under Indian climatic conditions. The corresponding specific power and exergy efficiency are found to be 80.5 kW and 39.77 % respectively. Under same operating conditions, the maximum net power output of 82.24 kW can be achieved at 0.92 ammonia concentration at the turbine inlet. The present analysis gives lot of insight to understand the design parameters to utilize geothermal energy.

INTRODUCTION

As the energy demand is increasing day by day, power generation industry plays a major role for the economic growth of any country. The rapid use of fossil fuels are not only causing the conventional energy resources to diminish faster but also leading to the environmental degradation. Considerable efforts have been undertaken for generating power by utilizing low temperature heat sources such as gas turbine exhaust, heat from internal combustion engines, waste heat from industrial process etc. The use of ammonia-water binary mixture as working fluid has favourable characteristics for utilizing heat and generating electricity from low-temperature heat sources. 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 effectively [1,2]. Kalina Cycle is mainly a modified Rankine cycle [3]. Many versions of Kalina cycle system have been proposed applicable to the different types of heat sources for power production [4-12]. The study of heat recovery from the gas turbine exhaust with Kalina bottoming cycle and the advantage over steam bottoming cycle is highlighted [13].

NOMENCLATURE

m	[kg/sec]	Mass flow rate
T	[K]	Temperature
h	[kJ/kg]	Specific enthalpy
s	[kJ/kg K]	Specific entropy
e	[kJ/kg]	Specific exergy
c_p	[kJ/kg K]	Specific heat
Q	[Kw]	Heat transfer
W	[Kw]	Work done
x	[-]	Ammonia mass fraction
F	[-]	Vapor fraction
AP	[K]	Approach point
PP	[K]	Pinch point
Special characters		
η		Efficiency
Subscripts		
$hrvg$		Heat recovery vapor generator
bp		Bubble Point
o		dead state
hf		Hot fluid
t		Turbine
g		Generator
p		Pump

The analysis of the cycle and the performance characteristics for a low temperature Kalina power plant using solar energy has been investigated [14]. In the present work, the use of geothermal brine as source fluid for generating electric power is proposed. The Kalina cycle system is modelled and the performance analysis is carried out for producing electricity by utilizing geothermal resources at Indian climatic conditions. The effect of ammonia concentration at the turbine inlet is investigated in detail and the optimum operating parameters for the proposed plant model are determined for the maximum cycle efficiency.

SEPARATION OF AMMONIA-WATER MIXTRURE

The properties of binary mixture depends upon three parameters i.e. pressure, temperature and concentration. The thermodynamic properties of ammonia-water mixture are calculated using Gibbs free energy equations.

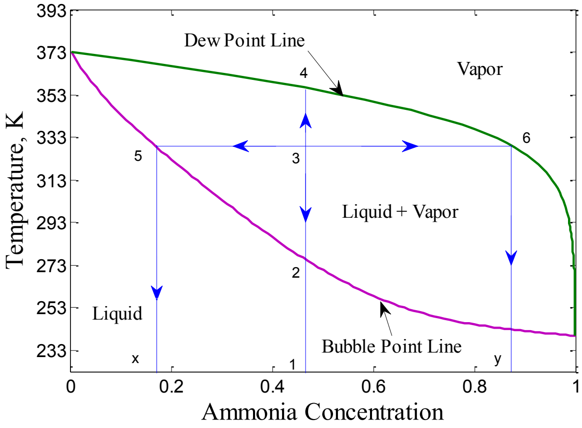

Figure 1 Phase equilibrium diagram for ammonia-water mixture at 1.013 bar

It is assumed that the superheated ammonia-water mixture in the vapor phase above the saturation temperature of water behaves as an ideal solution. Heat is supplied in the boiler or heat recovery vapor generator. The temperature of ammonia-water mixture increases steadily and the mass fraction of the solution remains constant till the start of the evaporation. The temperature at which the first vapor bubble appears is known as bubble point temperature of the mixture and is a function of pressure and concentration. Upon further heating the temperature rises continuously and finally at one particular temperature the last drop of liquid vaporizes. The temperature at which the last drop of liquid vaporises is known as dew point temperature of the mixture. Figure 1 shows the phase equilibrium diagram of ammonia-water mixture. The plot is obtained by joining all the bubble and dew points evaluated at ammonia concentration ranging from 0 to 1 at constant pressure. The loci of bubble points is called the bubble point line or the saturated liquid line and the loci of dew points are called the dew point line or the saturated vapor line of the mixture. The ammonia-water mixture is passed through the heat recovery vapor generator in such a way that the exit condition lies in the two phase region. The two phase mixture is then separated in the adiabatic separator.

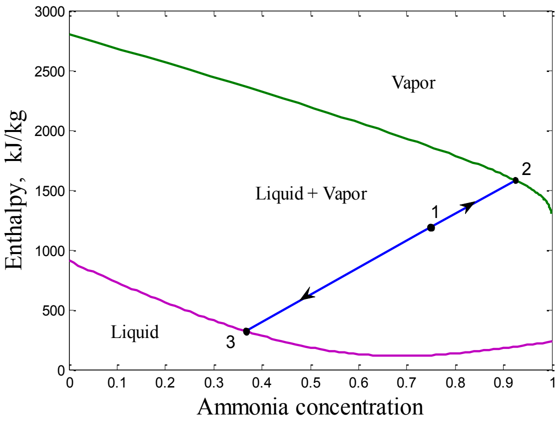

Figure 2 Phase diagram for separation of ammonia-water mixture at 35 bar and 398 K

The separation of ammonia-water mixture in the separator is depicted in Figure 2. Point 1 indicates the state of the mixture at the inlet of the separator. The ammonia concentration in vapor and liquid mixture is depicted corresponding to state point 2 and 3 on the saturated vapor and liquid lines. It is found that the performance of the ammonia-water based power plant is predominantly influenced by the separator parameters and hence the separator Pressure, temperature, vapor concentration are considered for investigation. Among the three parameters while one parameter is fixed, the other two are varied and the influence of these parameters on the plant performance is analyzed.

SYSTEM DESCRIPTION AND MODELING

The schematic flow diagram of low temperature Kalina cycle system is shown in Figure 3. Ammonia-water mixture is used as working fluid in the cycle. The heat from geothermal brine is recovered in the heat recovery vapor generator. The working fluid at state point 9 is separated into ammonia-rich vapor mixture and weak liquid mixture in the separator. The vapor mixture at state point 1 is expanded in the turbine to generate electric power. The fluid from the turbine exit rejects heat in the low temperature heat exchanger. The high pressure liquid mixture from the separator is throttled to low pressure after rejecting heat in the high temperature heat exchanger. The turbine exit fluid is mixed with the liquid mixture coming from the separator in the mixer and then condensed to a saturated liquid state in the condenser. The condensate is pumped to the heat recovery vapor generator after pre-heating in the low and high temperature heat exchangers to complete the cycle. The cycle repeats for the continuous power generation. The separator pressure is evaluated as a function of the separator temperature and ammonia concentration in the vapor mixture at the turbine inlet. The temperature of the liquid mixture at the state point 10 will be equal to the bubble point temperature and therefore the concentration of the liquid mixture is evaluated through iteration.

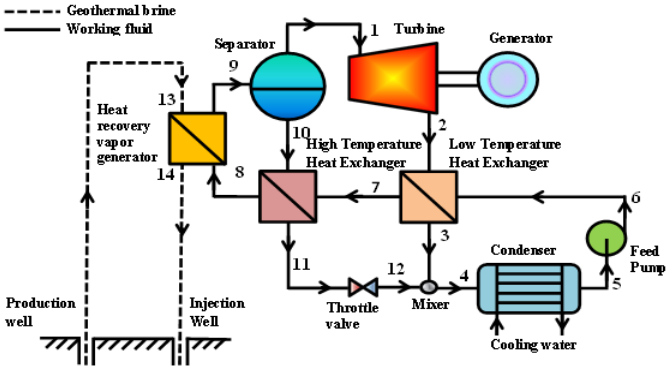

Figure 3 Schematic flow diagram of geothermal power plant based on Kalina cycle

The temperature range of geothermal brine used in the analysis is 393-423 K and the standard ambient temperature at the Indian climatic condition is 298 K. The terminal temperature difference at the heat recovery vapor generator is taken as 10 K. The pinch point and approach point and temperature difference are assumed to be 5 and 10 K. The isentropic efficiency and mechanical efficiency of turbine and feed pump are assumed as 75% and 96% respectively. The electricity generator efficiency is assumed as 98%. Pressure drop and heat loss in pipe lines are neglected.The pressure in the separator and condenser is determined from the temperature and concentration of the working fluid as it is the function of temperature and concentration at the saturated state. The turbine exit temperature is determined by entropy equalization for isentropic expansion and the actual temperature by the isentropic efficiency relation.

The vapor fraction in the separator is calculated by lever rule

$$F = (x_9 - x_{10})/(x_1 - x_{10}) \tag{1}$$

The temperature of strong solution at the inlet to the heat recovery vapor generator

$$T_8 = T_{bp} - AP \tag{2}$$

The temperature of the hot brine leaving the heat recovery vapor generator

$$T_{14} = T_{bp} + PP \tag{3}$$

The mass flow rate of hot fluid in the heat recovery vapor generator

$$m_{13} = m_9(h_9 - h_8)/c_{p_{hf}}(T_{13} - T_{14}) \tag{4}$$

The properties at all other state points are determined by mass, concentration and energy balance equations.

Work output of the turbine

$$W_{turbine} = m_1\,(h_1 - h_2)\eta_t\eta_g \tag{5}$$

The Work input to the pump

$$W_{pump} = m_5(h_6 - h_5)/\eta_p \tag{6}$$

Net output of the Kalina cycle

$$W_{net} = (W_{turbine} - W_{pump}) \tag{7}$$

Heat supplied in heat recovery vapor generator

$$Q_{hvrg} = m_8\,(h_9 - h_8) \tag{8}$$

Energy efficiency of the cycle

$$\eta_{cycle} = W_{net}/m_8\,(h_9 - h_8) \tag{9}$$

Specific exergy of the fluid

$$e = (h - T_o) - T_o(s - s_o) \tag{10}$$

Exergy efficiency of the cycle

$$\eta_{exergy} = W_{net}/m_{13}\,(e_{13} - e_{14}\,) \tag{11}$$

TRENDS AND RESULTS

The performance of the low temperature Kalina cycle system is thermodynamically investigated under the specified operating conditions. The influences of the turbine inlet concentration, strong solution concentration and turbine inlet temperature have been examined on the cycle efficiency, exergy efficiency and specific power. Results indicate an efficiency of 11.75 % with 0.95 and 0.70 ammonia concentrations at the turbine inlet and separator inlet respectively, operating at 418 K source temperature under Indian climatic conditions. The corresponding exergy efficiency and specific power are found to be 80.5 kW per kg/s and 39.77 %. Under same operating conditions, the maximum net power output is found to be 82.24 kW per kg/s at 0.92 turbine inlet concentration.

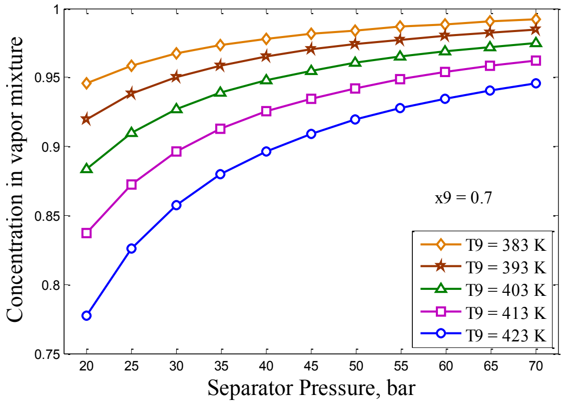

Figure 4 Effect of separator pressure on ammonia concentration in vapor mixture

Figure 4 shows the variation of ammonia concentration in vapor mixture at fixed separator inlet concentration. It is observed that as more ammonia evaporates at higher pressure, the concentration in vapor mixture increases with the increment in separator pressure. At higher separator temperature the ammonia concentration in vapor mixture varies rapidly in the beginning mainly due to higher evaporation rate of ammonia.

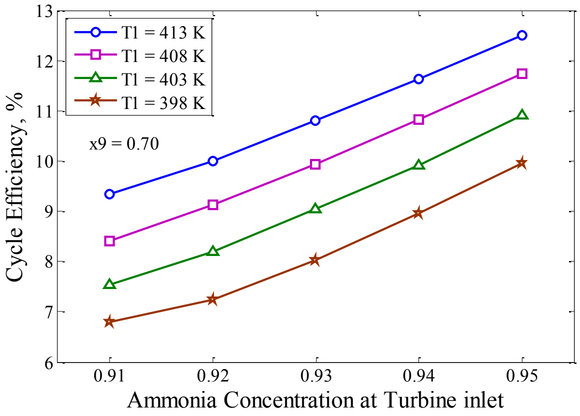

Figure 5 Effect of turbine inlet concentration on cycle efficiency at fixed separator inlet concentration

Figure 5 shows the cycle efficiency versus turbine inlet concentration with the separator inlet concentration of 0.70. The concentration at the turbine inlet is varied from 0.91 to 0.95 for turbine inlet temperatures of 398 K, 403 K, 408 K and 413 K. It can be seen that the cycle efficiency increases with ammonia concentration at the turbine inlet mainly due to rise in inlet pressure.

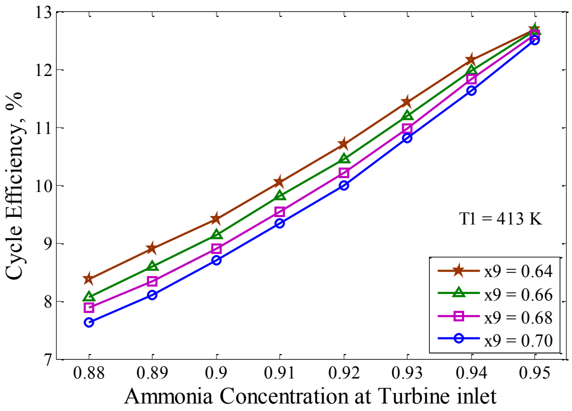

Figure 6 Effect of turbine inlet concentration on cycle efficiency at fixed separator temperature

The cycle efficiency versus turbine inlet concentration with the separator inlet temperature of 413 K is depicted in Figure 6. The concentration at the turbine inlet and the concentration at the separator inlet are increased by 0.01 and 0.02 respectively. The cycle efficiency increases with ammonia concentration at the turbine inlet. Figure 7 depicts the effect of turbine inlet concentration on specific power for turbine inlet temperatures of 393 K, 398 K, 403 K and 408 K. The ammonia concentration at the turbine inlet is ranged from 0.91 to 0.95 and the separator inlet concentration is constant, 0.70. The specific power increases slowly to a maximum value with turbine inlet concentration and then decreases. The optimum ammonia concentration at the turbine inlet exists according to the different temperatures at the turbine inlet.

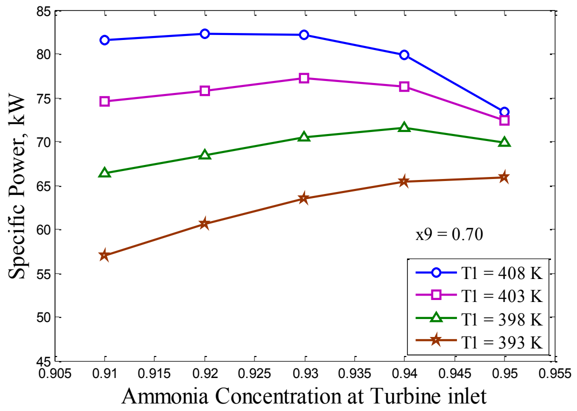

Figure 7 Effect of turbine inlet concentration on specific power at fixed separator inlet concentration

At turbine inlet temperature of 408K, the maximum specific power is increased to 82.24 kW per kg/s at 0.92 turbine inlet concentration. Figure 8 shows the influence of turbine inlet concentration on specific power at 413 K turbine inlet temperature. It can be seen that the specific power first increases slowly and reaches its maximum and then decreases with the increment in turbine inlet concentration, which is consistent for separator inlet concentration of 0.64, 0.66, 0.68 and 0.70. The ammonia concentration at the turbine inlet is ranged from 0.91 to 0.95 at 413 K turbine inlet temperature.

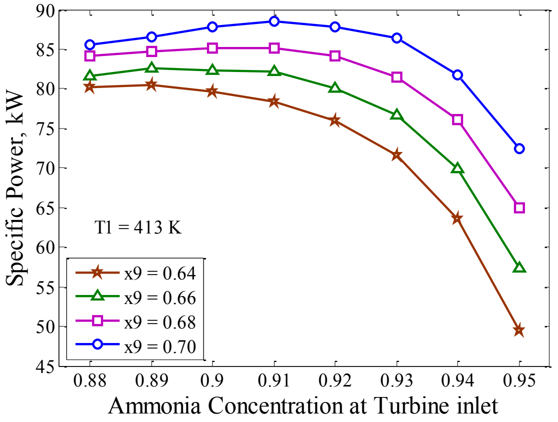

Figure 8 Effect of turbine inlet concentration on specific power at fixed separator temperature

The influence of separator inlet concentration and turbine inlet concentration on specific power and cycle efficiency with fixed separator temperature is depicted in Figure 9. Under specified limits of operating conditions, the system results 7.5- 12.75 % cycle efficiency. Figure 10 shows the specific power versus cycle efficiency with the separator inlet concentration of 0.70. The concentration at the turbine inlet is varied from 0.91 to 0.95 for turbine inlet temperatures of 398 K, 403 K, 408 K and 413 K. It can be seen that the cycle efficiency increases with the turbine inlet temperature.

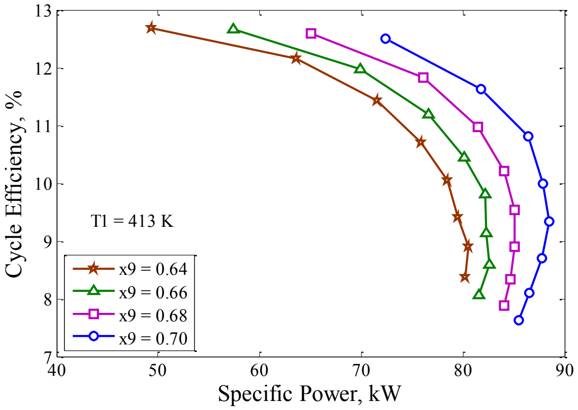

Figure 9 Variation of cycle efficiency with specific power at fixed turbine inlet temperature

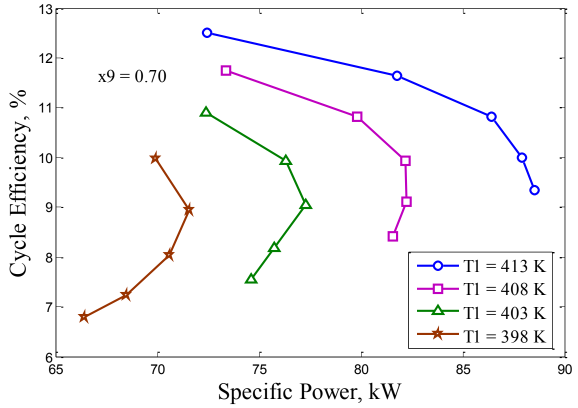

Figure 10 Variation of cycle efficiency with specific power at fixed separator inlet concentration

The specific power increases slowly and reaches its maximum and then decreases with the increment in turbine inlet concentration. It can be seen that the optimum turbine inlet concentration is different for maximum cycle efficiency and exists according to different turbine inlet temperature. Figure 11 depicts the exergy efficiency versus turbine inlet concentration with the separator inlet concentration of 0.70. The concentration at the turbine inlet is varied from 0.91 to 0.95 for turbine inlet temperatures of 398 K, 403 K, 408 K and 413 K. It can be seen that the cycle efficiency increases with ammonia concentration at the turbine inlet, which is mainly due to rise in inlet pressure. Under specified limits of operating conditions, the system results 29.50-40.75 % cycle efficiency.

Figure 12 shows the comparison of exergy destruction in plant components. The exergy destruction at separator, condensate feed pump, heat exchangers, heat recovery vapor generator, turbine, condenser, mixer, and throttle valve are found to be 0.43%, 0.19%, 18.58%, 31.43%, 3.17%, 1.0% 4.43% and 1% respectively. The total exergy destruction in the cycle is 60.23 and the exergy efficiency of the cycle is 39.77. The exergy analysis is carried out to determine the operating conditions of a system which destroys the least available work.

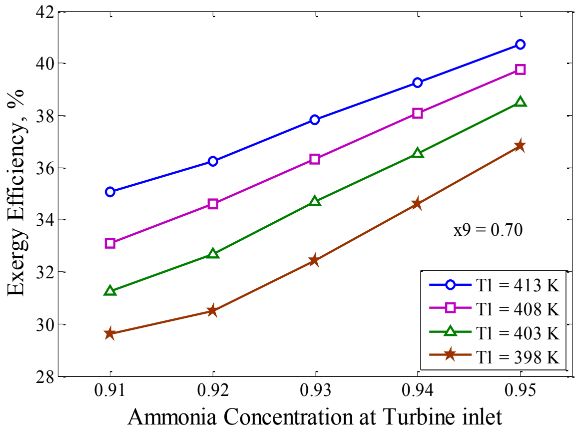

Figure 11 Effect of turbine inlet concentration on exergy efficiency at fixed separator inlet concentration

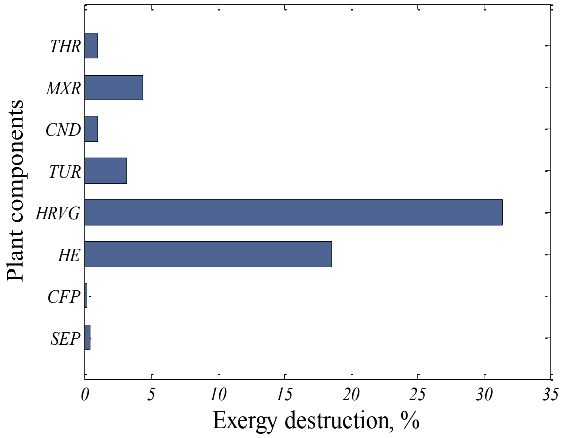

Figure 12 Exergy loss percentages of plant components; *SEP:* separator; *CFP:* condensate feed pump; *TUR:* turbine; *HE:* heat exchangers; *HRVG:* heat recovery vapor generator; *CND:* condenser; *MXR:* mixer; *THR:* throttle valve

The exergy study depicts the scope for improvement in heat recovery vapor generator and heat exchangers.

Table 1 Specifications of the geothermal plant at 408 K separator temperature

Sl. no.	Description	Result
1	Work output of turbine, kW	80.5
2	Work input to condensate feed pump, kW	7.18
3	Net electricity output, kW	73.32
4	Heat load in condenser, kW	562
5	Heat load in low temperature regenerator, kW	71
6	Heat load in high temperature regenerator, kW	225
7	Heat load in heat recovery vapor generator, kW	624
8	Kalina cycle energy efficiency, %	11.75
9	Kalina cycle exergy efficiency, %	39.77

Table 2 Kalina cycle material flow details with respect to Figure 3 at 408 K separator temperature

State	Temperature, K	Pressure, bar	Ammonia concentration	Flow rate, kg/sec	Specific enthalpy, kJ/kg	Specific entropy, kJ/kgK	Specific exergy, kJ/kg
1	408.0	48.54	0.95	0.44	1503.96	4.31	217.83
2	332.3	7.50	0.95	0.44	1309.82	4.52	-37.81
3	308.9	7.50	0.95	0.44	1149.04	4.03	-51.71
4	322.3	7.50	0.70	1.00	500.69	1.82	-40.84
5	303.0	7.50	0.70	1.00	-61.47	0.13	-99.16
6	303.9	48.54	0.70	1.00	-54.58	0.26	-133.24
7	319.3	48.54	0.70	1.00	16.28	0.34	-84.30
8	368.9	48.54	0.70	1.00	258.33	1.03	-49.21
9	408.0	48.54	0.70	1.00	882.39	2.51	135.14
10	408.0	48.54	0.50	0.56	392.59	1.09	68.75
11	324.3	48.54	0.50	0.56	-10.32	0.02	-16.73
12	324.8	7.50	0.50	0.56	-10.22	0.03	-19.59
13	418.0	-	-	3.82	610.38	1.80	73.10
14	378.9	-	-	3.82	443.85	1.38	31.25

Table 1 gives the results of the Kalina cycle system defined in Figure 3 at 408 K separator temperature under Indian climatic conditions. The specifications of the plant components, power and efficiency are developed for unit mass of the working fluid. Table 2 shows the properties of the working and source fluid at various state points. A unit mass of working fluid in the power cycle demands 3.82 units of source fluid for the stated conditions. The results have been validated by using the previously published data under the similar operating conditions [14]. The comparison of the simulated work with the plant readings can be seen in table 3.

Table 3 Comparison of present work with the existing readings in Ref. [14] at 408K separator temperature

Sl. no.	Description	Simulation	Ref.[14]
1	Hot water requirement, kg/s	3.82	3.47
2	Hot water inlet temperature, K	408	408
3	Hot water outlet temperature, K	378.9	365.5
4	Separator pressure, bar	48.54	35.6
5	Low pressure, bar	7.5	7.5
6	Strong solution concentration	0.70	0.70
7	Separator liquid concentration	0.50	0.47
8	Vapor in separator, kg/s	0.44	0.48
9	Temperature after expansion, K	59.3	66.4
10	Turbine output, kW	80.5	86.6
11	Pump input, kW	7.18	10.6
12	Cycle energy efficiency	11.75	10.0

CONCLUSION

The Kalina cycle presents a host of new ideas to the power generating industry. The combined higher efficiency and lower cost advantages of Kalina cycle makes the exploitation of new energy resources possible. Kalina cycle for utilizing the geothermal energy in India is put forward. It has been modelled thermodynamically and analyzed parametrically. The energy and exergy efficiencies are evaluated and the variation tendency is analyzed. It emerges that, for a given turbine inlet temperature, there exist an optimum ammonia concentration at the turbine inlet that yields maximum power output. The cycle efficiency increases with an increase in turbine inlet concentration and also corresponding to the much richer ammonia-water mixture at the separator inlet. The maximum cycle efficiency does not necessarily yield the optimum operating conditions for the system. Though the cycle efficiency increases slightly at higher concentration, there will be difficulty in operation and control of the plant at high pressure. The highest electrical power output for Kalina cycle system if it were applied in India, could be achievable using 92% ammonia concentration at the turbine inlet and 7.5 bar exit pressure from turbine.

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