International Journal of Thermal Technologies
E-ISSN 2277 – 4114

Available at http://inpressco.com/category/ijtt/

Research Article

Thermal Performance of Geothermal Power Plant with Kalina Cycle System

K. Deepak[Ȧ*] and A.V.S.S.K.S. Gupta[Ḃ]

[Ȧ]Department of Mechanical Engineering, Vardhaman College of Engineering, Hyderabad- 501 218, India
[Ḃ]Department of Mechanical Engineering, J N T U College of Engineering, Hyderabad - 500 072, India

Accepted 10 May 2014, Available online 01 June2014, **Vol.4, No.2 (June 2014)**

Abstract

With the advent of Kalina cycle, researchers are focusing on the development of new cycle configurations for the utilization heat energy from low temperature heat sources which might have otherwise not utilized. A model of low temperature Kalina cycle system is investigated for generating electricity from geothermal source. The thermodynamic properties of ammonia-water mixture are computed using Gibbs free energy equations. A computer code is developed to determine the cycle performance and properties of ammonia-water mixture at different operating conditions. The thermodynamic analysis of ammonia concentration at the turbine inlet on cycle performance is presented. A maximum efficiency of 11.77 % is achieved at separator temperature 125°C and 95% turbine inlet concentration. Also a maximum specific power of 74.32 kW is achieved at separator temperature 125°C and 92% turbine inlet concentration. This work provides an insight to the researchers for developing new configurations of Kalina cycle systems based on the available heat sources.

Keywords: *Ammonia-water mixture, Geothermal power, Kalina cycle system, Low temperature heat utilization*

1. Introduction

The use of ammonia-water binary mixture as working fluid has favourable characteristics for utilizing heat and generating electricity from low-temperature heat sources. There is an increased curiosity to design innovative, cost-effective, efficient and reliable energy conversion systems with the Kalina cycle technology. The gain in efficiencies over the Rankine cycle particularly in the medium to low temperature range makes the Kalina cycle ideal for industrial waste heat, solar, geothermal and combined cycle power generating applications. In Kalina cycle system, heat is transferred to the ammonia-water mixture either through the heat exchanger or boiler tubes. The ammonia-water mixture entering the separator exists in two-phase region. This means that the saturated vapor coexists in equilibrium with the saturated liquid and as such the concentrations of ammonia in the liquid and vapor phase are different. The high pressure vapor mixture from separator is then passed through a conventional steam turbine to generate electric power.

The analysis of ammonia-water mixture based power generation systems require thermodynamic properties of ammonia-water mixture at various conditions of pressure, temperature and concentration. (Ziegler and Trepp, 1984) used Gibbs free energy equation and described an equation for the thermodynamic properties of ammonia and water mixture. (El-Sayed and Tribus, 1985) have reviewed and extended data on properties of ammonia-water mixture up to 316 °C and 210 bar. (Patek and Klomfar, 1995) used a set of five equations to determine the vapour-liquid equilibrium properties of ammonia-water mixture avoiding iterations. (Nag and Gupta, 1997) used the Peng-Robinson equation for the vapor-liquid equilibrium. (Tamm et al, 2003) presented the feasibility of vapor generation and absorption condensation process experimentally. (Srinivas et al, 2008) studied the heat recovery from the gas turbine exhaust with Kalina bottoming cycle and highlighted the advantage over steam bottoming cycle. (Shankar Ganesh and Srinivas, 2011) selected the strong solution concentration as a key parameter and presented the performance characteristics for low temperature Kalina power plant using solar energy.

From the literature it is identified that the turbine inlet concentration is the key parameter which influences the performance of the Kalina cycle systems. The performance of the binary mixture power plant with respect to turbine inlet concentration is not well reported in the literature. The main objective of the current work is to analyse the performance of geothermal power plant for generating electricity and to fetch the development of new configurations of the Kalina cycle systems. The ammonia concentration in the working fluid is taken as 0.64 which resulted in maximum cycle efficiency.

2. Modelling of Kalina cycle

Fig. 1 shows the schematic flow diagram of low temperature Kalina cycle system. The heat from the geothermal fluid is recovered in the heat recovery steam

*Corresponding author: **K. Deepak**

DOI: http://dx.doi.org/10.14741/ijtt/2014.4.2.04

generator (8–9). The working fluid is separated into ammonia-rich vapor mixture (10) and weak liquid mixture (9) in the separator. The vapor from the separator is super-heated before passing it to the turbine. The vapor at (1) is expanded in the turbine to generate electric power.

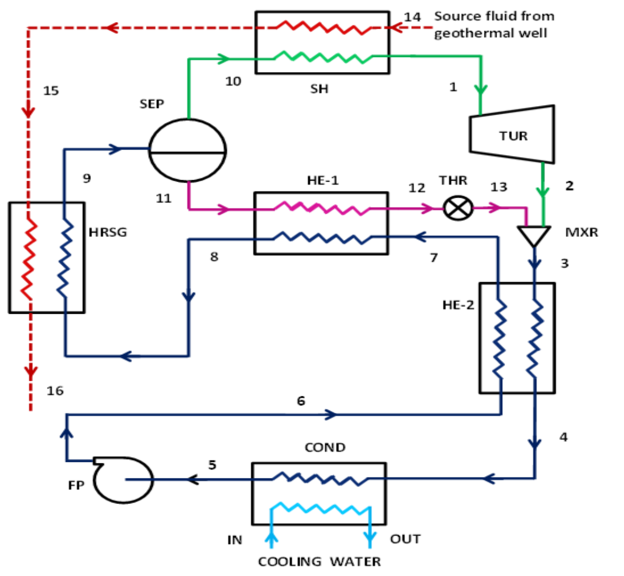

Fig. 1 Schematic diagram of geothermal power plant operating on Kalina cycle; HRSG: heat recovery steam generator; SEP: separator; TUR: turbine; THR: throttle; MXR: mixer; HE: heat exchanger; COND: condenser.

The weak liquid mixture coming from separator has been throttled (12–13) and mixed with turbine exit fluid in the mixer (3). It is then passed through the low temperature heat exchanger (3–4) and condensed to a saturated liquid state in the condenser (5). The condensate is pumped to separator pressure (6) and heated in the low temperature heat exchanger (6–7) and in high temperature heat exchanger (7-8). The preheated liquid mixture (8) is converted into liquid vapor mixture (9) in the heat recovery steam generator. It is then supplied to separator where liquid and vapor mixture is separated. The cycle repeats for the continuous power generation. The working fluid at the separator exit (1) is in a saturated vapor condition. The separator pressure (10) can be determined from the separator temperature and vapor concentration as it is the function of temperature and concentration at the saturated vapor state. The temperature (11) at the liquid outlet in the separator is equal to bubble point temperature. From this assumption, the liquid portion concentration x_{11} can be determined through iteration. The Kalina cycle is solved with 1 kg/s of strong solution at the separator inlet (9). Out of one kg/s mixture in the separator, F kg/s is the vapor portion and 1-F kg/s is the liquid portion separated.

3. Thermodynamic Analysis

Pressure drop and heat loss in pipe lines are neglected. The condensate leaving the condenser is assumed to be saturated liquid. The temperature of the hot brine leaving the heat recovery vapor generator

$$T_{16} = T_b + PP \quad (1)$$

Table 1 Kalina cycle system specifications and conditions

S. No	Parameter	Value
1	Source fluid temperature	145 °C
2	Ambient Temperature	23° C
3	Degree of super heat	10 °C
4	Pinch point in steam generator, PP	5° C
5	Terminal temperature difference	10 °C
6	Generator efficiency, η_g	98 %
7	Isentropic efficiency of pump and turbine, η_i	75 %
8	Mechanical efficiency of the pump and turbine, η_m	96 %

The vapor fraction is calculated by applying lever rule,

$$F = (x_9 - x_{11})/(x_{10} - x_{11}) \quad (2)$$

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

$$T_8 = T_7 + (1 - F) * (T_9 - T_7) \quad (3)$$

The low pressure is determined from mixture concentration x_5 and temperature T_5 at condenser outlet. The unknown properties i.e. temperature, concentration and mass flow rates are determined by mass, concentration and energy balance equations. The turbine exit temperature can be determined by entropy equalization for isentropic expansion and the actual temperature by the isentropic efficiency relation.

Work output of the turbine

$$W_t = m_1 (h_1 - h_2)\eta_t\eta_g \quad (4)$$

The work input to the pump

$$W_p = m_5(h_6 - h_5)/\eta_p \quad (5)$$

Net output of the cycle

$$W_{net} = (W_t - W_p) \quad (6)$$

Heat supplied in heat recovery steam generator

$$Q_{hrsg} = m_8(h_9 - h_8) + m_{10}(h_1 - h_{10}) \quad (7)$$

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

$$m_{14} = \frac{(m_8(h_9 - h_8) + m_{10}(h_1 - h_{10}))}{C_h(T_{14} - T_{16})} \quad (8)$$

Efficiency of the cycle

$$\eta_{cycle} = W_{net}/Q_{hrsg} \quad (9)$$

4. Results and Discussion

The low temperature Kalina cycle system model is thermodynamically investigated under the operating conditions. The influence of the turbine inlet concentration, strong solution concentration and separator temperature have been examined on the cycle efficiency and specific power.

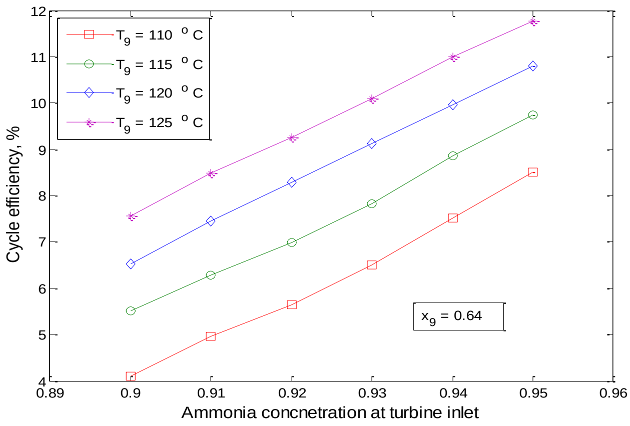

Fig. 2 Variation of cycle efficiency with turbine inlet concentration

The current model results 11.77 % cycle efficiency at separator temperature of 125°C and 95% vapor concentration. Fig. 2 depicts the effect of turbine inlet concentration on cycle efficiency at separator inlet concentration of 0.64. The concentration at the turbine inlet is varied from 0.9 to 0.95 for separator temperatures of 110°C, 115°C, 120°C and 125°C. It can be seen that the cycle efficiency increases with ammonia concentration at the turbine inlet mainly due to the rise in inlet pressure.

Table 2 Fluid flow details in Kalina cycle system with respect to Fig. 1 at source temperature of 145°C

State	Pressure (bar)	Ammonia Concentration	Temperature (°C)	Enthalpy (kJ/kg)
1	35.7	0.95	135.0	1550.0
2	6.5	0.95	61.5	1340.9
3	6.5	0.64	53.5	4599.8
4	6.5	0.64	48.5	380.9
5	6.5	0.64	30.5	-83.7
6	35.7	0.64	30.5	-79.0
7	35.7	0.64	47.5	-1.1
8	35.7	0.64	98.0	244.6
9	35.7	0.64	125.0	768.0
10	35.7	0.95	125.0	1518.0
11	35.7	0.48	125.0	341.6
12	35.7	0.48	52.5	-4.6
13	6.5	0.48	53.0	-4.5

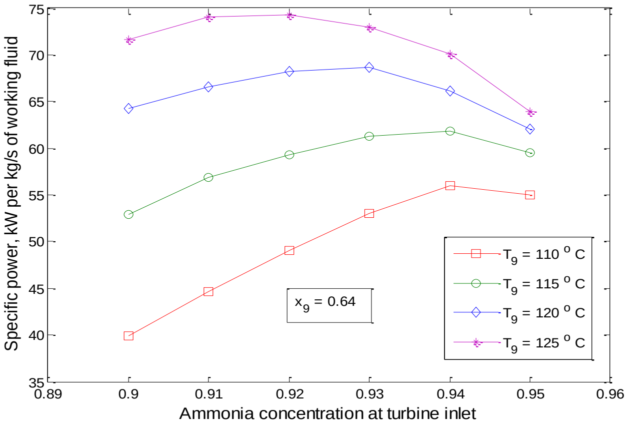

Fig. 3 Variation of specific power based on working fluid with turbine inlet concentration

The effect of turbine inlet concentration on specific power based on working fluid at separator inlet concentration of 0.64 is depicted in Fig. 3. The turbine inlet concentration is varied from 0.9 to 0.95 with an increment of 0.01. It has been perceived that there exists an optimum value of turbine inlet concentration which yields maximum specific power. A maximum specific power of 74.32 kW is achieved at separator temperature 125°C and 92% turbine inlet concentration.

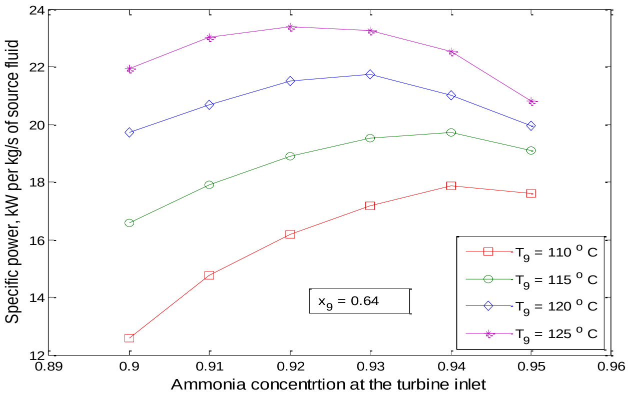

Fig. 4 Variation of specific power based on source fluid with turbine inlet concentration

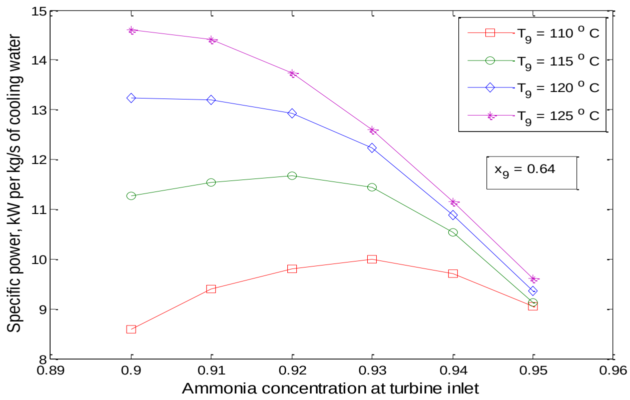

Fig. 5 Variation of specific power based on cooling water with turbine inlet concentration

The influence turbine inlet ammonia concentration on specific power per kg of source fluid is depicted in Fig. 4. The ammonia concentration is varied from 0.9 to 0.95. The trend is found to be similar as in the case of specific power based on the working fluid. The effect of turbine inlet concentration on specific power based on cooling water is depicted in Fig. 5. The higher value of ammonia concentration at the turbine inlet demands large quantity of cooling water to be supplied and hence the specific power per kg of cooling water is found to be decreasing at higher values of ammonia concentration.

Conclusions

The equations for energy interactions in the plant components are developed to evaluate the performance of the cycle. The Kalina cycle presents a host of new ideas to the power industry. Because of its higher efficiency, the physical size of certain plant components will be smaller.

Smaller boilers, smaller pollution control systems, smaller fuel handling systems, smaller ash handling systems, and smaller cooling systems will be required for a given power output. The combined higher efficiency and lower cost advantages of Kalina cycle makes the exploitation of new energy resources possible.The performance of the geothermal Kalina cycle system at different combinations of source temperature and turbine inlet concentration is assessed. The cycle efficiency increases with increase in vapor mixture and increases with the increase in the separator pressure. With the increase in separator temperature, the concentration of vapor mixture decreases at the fixed pressure. In order to obtain higher vapor concentration the separator pressure is to be increased.

Nomenclature

P pressure, bar
T temperature, ^{o} C
C Specific heat, J/kg K
F vapor fraction
x ammonia mole fraction in liquid phase

Subscripts

b bubble point
h hot fluid
t turbine
p pump
hrsg Heat recovery vapor generator

References

B. Ziegler, C. Trepp, (1984), Equation of state for ammonia–water mixtures, *International Journal of Refrigeration*, vol. 7, No. 2, pp. 101–106.

Y. M.EL-Sayed, M. Tribus, (1985), A theoretical comparison of Rankine and Kalina cycles, *ASME publication*, AES: vol. 1.

J. Patek and J. Klomfar, (1995),Simple functions for fast calculations of selected thermodynamic properties of the ammonia-water system, *Refrigration*, 18: 228-234.

P. K. Nag, A. V. S. S. K. S. Gupta, (1997), Exergy analysis of the Kalina cycle, *Applied Thermal Engineering*, vol. 18, No. 6, pp. 427-439

F. Xu, D. Y. Goswami, (1999), Thermodynamic properties of ammonia water mixtures for use in power cycles, *Energy*. Vol. 24, pp. 525-536.

G. Tamm, D. Y. Goswami, S. Lu, A. A. Hasan, (2003), Novel combined power and cooling thermodynamic cycle for low temperature heat sources, part 1: theoretical investigation. *ASME J Sol Energy Eng*. vol. 125, No. 2, pp. 218–222.

G. Tamm, D. Y. Goswami, (2003), Novel combined power and cooling thermodynamic cycle for low temperature heat sources", part 2: experimental investigation. *ASME J Sol Energy Eng.* vol. 125 No. 2, pp. 223–229.

T. Srinivas, A. V. S. S. K. S. Gupta, B. V. Reddy, (2008),Performance simulation of combined cycle with Kalina bottoming cycle, *Cogeneration and Distributed Generation Journal* vol. 23, No. 1, pp. 6–20.

N. Shankar Ganesh, T. Srinivas, (2012), Design and modeling of low temperature solar thermal power station, *Applied energy*, vol. 9, No. 1, pp. 180 – 1