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Comparative study of augmentation in low temperature Kalina cycle systems

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ABSTRACT

Kalina cycle systems are being investigated intensively for harnessing energy from low and medium temperature energy resources. Ammonia and water binary mixture of varied concentration is being used as working substance in these systems. The non-isothermal boiling nature of the ammonia-water solution has the advantage of reducing the structural losses in the cycle. The present work is aimed to compare the performance of the Kalina cycle system by increasing the ammonia concentration in the vapor mixture. An auxiliary separator is incorporated for this purpose and the separation process is explained on the h-s diagram. The increase in ammonia concentration has led to the decrease in the mass flow rate and as well as enthalpy of the vapor mixture. Comparison of cycle performance with single and double separator systems has been made. The influence of separator temperature and ammonia mass fraction in the basic solution on cycle efficiency and specific power is investigated for both systems. Higher ammonia mass fraction at turbine inlet leads to higher cycle efficiency for ammonia mass fraction in the basic solution higher than 0.6 and separator temperature lesser than 110 ° C.

Keywords: *- Kalina cycle; ammonia-water mixture; ammonia mass fraction; geothermal energy utilization*

I. 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].The analysis of the cycle and the performance characteristics for a low temperature Kalina power plant using solar energy has been investigated [14]. The performance of gas turbine-steam turbine combined cycle power plants have been studied and the degree of augmentation has been compared [15].In the present work, the use of low temperature heat resources for generating electric power is proposed. Anew Kalina cycle system is modelled and the performance analysis is carried out for producing electricity by utilizingheat from low temperature resource at Indian climatic conditions. An auxiliary separator is added in the system in order to enhance the vapor mass fraction at the turbine inlet.

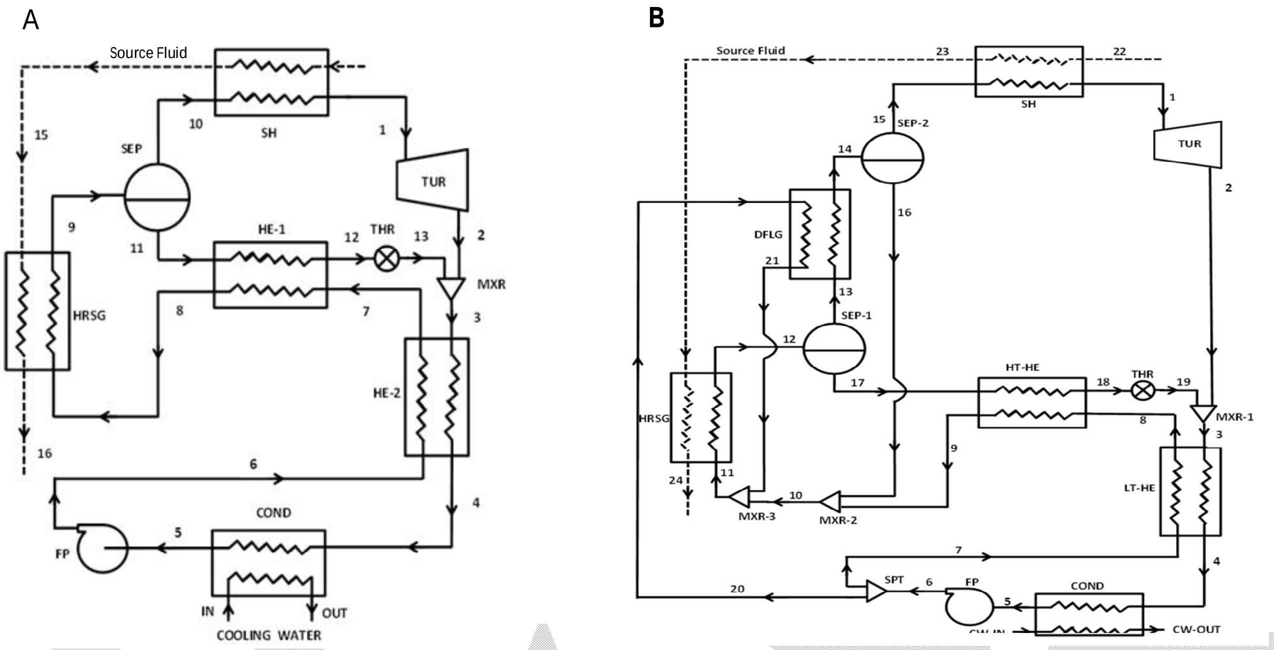

Figure 1.Schematic diagrams of Kalina cycle systems. A: with single separator; B: with double separator.

II. METHODOLOGY

Figure 1 shows the schematic diagram of low temperature Kalina cycle systems with single and double separators.The influence of ammonia concentration in the basic solution and separator temperature is investigated in detail and the optimum operating parameters for the proposed plant model are determined for the maximum cycle efficiency. The system modelling and analysis are presented in the following sections.

III. SYSTEM MODELLING AND DESCRIPTION

Kalina cycle systems generally consists of heat recovery steam generator, Separator, Superheater, Turbine, Mixer, Throttle valve, Condenser and Heat exchanger. Figure 1-A shows the Kalina cycle system model with single separator. The heat from the source fluid is recovered in the heat recovery steam generator. The working fluid at state point 9 is separated into ammonia-rich vapor mixture and weak ammonia-water solution in the separator. The vapor mixture from state point 10 is the heated in the superheater to state point 1. The vapor mixture from 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. Figure 1-B shows the proposed model for Low temperature Kalina cycle system. In this system the vapor mixture originating from the separator at state point 13 is vapor concentration. The vapor is enriched by condensing the moisture content present in it and separating out. The enriched vapor mixture from state point 15 is heated in the super heater to state point 1 passed through a dephlegmator to enrich the and then expanded in the turbine to produce torque. The high pressure liquid mixture from the feed pump is split into two streams. One of the streamsat state point 20 is passed through the dephlegmator to condense the moisture content in the vapor mixture passing through it.The enrichment of mass fraction in vapor mixture is depicted in Figure 2. In this figure, State point 12 indicates the state of the strong solution at the inlet of the separator-1 in Figure 1-B. The state of the vapor mixture and weak solution is represented by State point 13 and 17.

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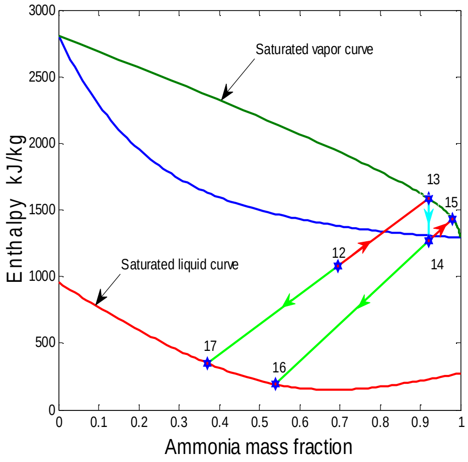

Fig. 2 Sepration process of ammonia-water mixture

Process 13-14 represents cooling of the vapor mixture in the dephlegmator. The mass fraction remains constant during this process. The state of the working fluid at the inlet of the separator-2 is represented by state point 14. State point 15 and 16 represents the state of the vapor and liquid mixture after separation.

IV. THERMODYNAMIC ANALYSIS

Referring to the Figure 1-A, the degree of super heat for superheating saturated vapor mixture is assumed as 10 ° C. 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 11 will be equal to the bubble point temperature and therefore the concentration of the liquid mixture is evaluated through iteration. The separator temperature range used in the analysis is 95-130° C and the standard ambient temperature at the Indian climatic condition is 28 ° C. The terminal temperature difference at the heat recovery vapor generator is taken as 10 ° C. The pinch point and approach point and temperature difference are assumed to be 5 and 10 ° C. 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 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

$$F = (x_9 - x_{11})/(x_{10} - x_{11}) \qquad (1)$$

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

$$T_8 = T_{bp} - AP \qquad (2)$$

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

Work output of the turbine

$$W_{turbine} = m_1 (h_1 - h_2)\eta_t\eta_g \qquad (3)$$

The Work input to the pump

$$W_{pump} = m_5(h_6 - h_5)/\eta_p \qquad (4)$$

Net output of the Kalina cycle

$$W_{net} = (W_{turbine} - W_{pump}) \qquad (5)$$

Heat supplied in heat recovery steam generator

$$Q_{hrsg} = m_8 (h_9 - h_8) \qquad (6)$$

Energy efficiency of the cycle

$$\eta_{cycle} = W_{net}/m_8 (h_9 - h_8) \qquad (7)$$

V. RESULTS AND DISCUSSIONS

The performance of the low temperature Kalina cycle systems both with single and double separator is thermodynamically investigated for the specified operating conditions. A computer program has been coded allowing calculation of thermodynamic properties and data analysis. The program handles data analysis efficiently and provides clear comparison to expected results. The influences of separator temperature and ammonia mass fraction have been examined for cycle efficiency and specific power. The results are plotted on the graphs for comparison. The results of the parametric analysis have been presented in the form of plots. The effect of separator temperature on cycle efficiency is depicted in Figure 3. The performance was compared taking the value of ammonia mass fraction in the basic solution as 0.45. The ammonia mass fraction in vapor was fixed at 0.92. For every ammonia mass fraction value in the basic solution there exist an optimum separator temperature for which the efficiency is maximum.

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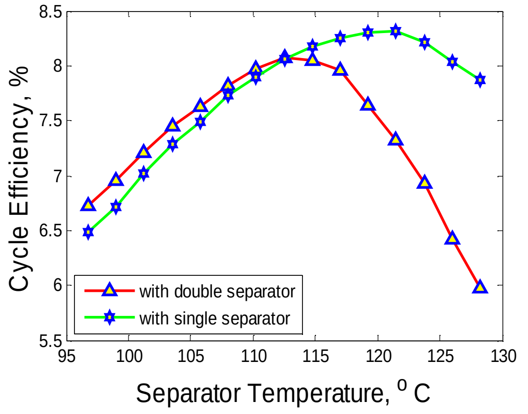

Fig.3 Variation of cycle efficiency with separator temperature

Further the efficiency increases with increase in ammonia mass fraction in the basic solution. For 0.45 ammonia mass fraction in the basic solution, the maximum efficiency of 8.32 % can be obtained at 121.5°C separator temperature with single separator system. Whereas with double separateor system, the maximum efficiency of 8.07 can be obtained at 112.0 °C separator temperature.

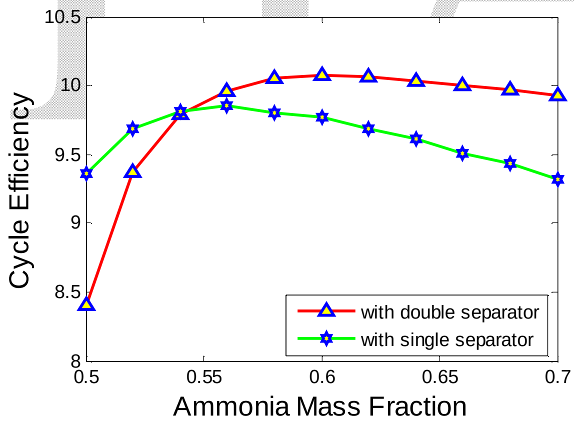

Fig. 4V ariation of cycle efficiency with ammonia mass fraction in basic solution.

The effect of ammonia mass fraction in basic solution on cycle efficiency is depicted in Figure 4. The performance was compared for spearator temperature of 130 o C. The ammonia mass fraction in vapor was fixed at 0.92. It has been observed that the efficiency rises with the ammonia mass fraction, reaches a peak value and decreases further.

For every separator temperaure in the feasible region there exist an optimum ammonia mass fraction for which the efficiency is maximum. Further the efficiency increases with increase in separator temperature. For 130 o C separator temperature, the maximum efficiency of 9.85% can be obtained at 0.56 ammonia mass fraction with single separator system. Whereas with double separateor system, the maximum efficiency of 10.07 can be obtained at 0.6 ammonia mass fraction.

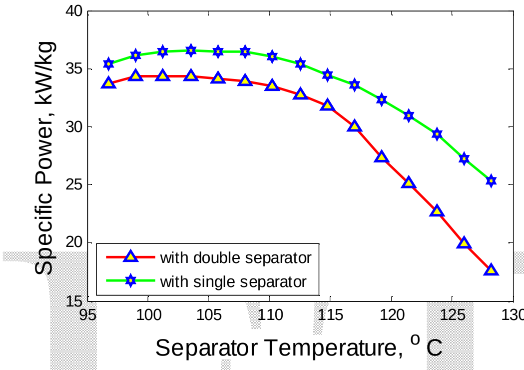

Fig. 5 Variation of specific power with separator temperature

Figure 5 shows the effect of separator temperature on specific power at fixed ammonia mass fraction in the basic solution. The separator temperature is varied ranging from 95-130 ^{o} C. The performance was compared for 0.45 ammonia mass fraction in the basic solution while the ammonia mass fraction in vapor was fixed at 0.92. It has been observed that the specific power rises with the separator temperatue, reaches a peak value and decreases. For every ammonia mass fraction value in the basic solution there exist an optimum separator temperature for which the specific power is maximum. Further the specific power increases with increased ammonia mass fraction in the basic solution. For 0.45 mass fraction, the maximum specific power of 36.55 kW can be obtained at 103.05 ^{o} C separator temperature with single separator. Where as with double separateor system, the maximum specific power of 34.38 kW can be obtained at 103.05 ^{o} C It has also been found that the optimum temperature for maximum efficiency and specific power are different.The effect of ammonia mass fraction at the separator inlet on specific power is depicted in Figure 6. The performance was compared for spearator temperature of 130 ^{o} C. The

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ammonia mass fraction in vapor was fixed at 0.92. It has been observed that the specific power rises with the ammonia mass fraction. Further the efficiency increases with increase in separator temperature. The decrease in specific power in double separator system is due to the decrease in vapor mass in the dephlegmator. **Table 1** shows the specifications of the Kalina cycle system with single and double separator developed for unit mass of the working fluid. The ammonia mass fraction in the basic solution and vapor mixture has been taken as 0.7 and 0.95. The separator temperature is fixed at 125 ^{o} C while degree of superheat is limited to 10 ^{o} C.

S.No.	Description	Ref.[14]	Simulated results (A)	Simulated results (B)
1.	Separator pressure, bar	35.6	35.70	35.7
2.	Condenser pressure, bar	7.5	7.60	7.6
3.	Strong solution concentration	0.70	0.70	0.70
4.	Weak solution concentration	0.47	0.48	0.48
5.	Vapor in separator, kg/s	0.48	0.47	0.43
6.	Temperature after expansion, ^{o} C	66.4	65.7	45.5
7.	Turbine output, kW	86.6	87.25	85.01
8.	Pump input, kW	10.6	4.72	4.56
9.	Cycle energy efficiency	10.0	10.90	11.47

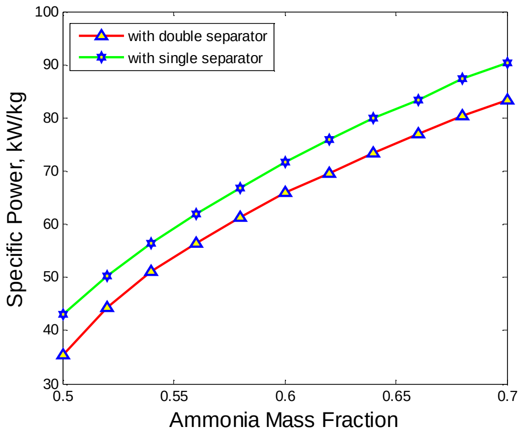

Fig. 6 Variation of specific power with basic solution ammonia mass fraction.

Table 1Comparison of present work with the existing plant readings [14] at 125 ^{o} C

The efficiency of the Kalina cycle system with double separator is found to be higher than single separator system. Due to decrease in vapor in separator, the turbine output decreased comparatively. A considerable decrease in temperature after expansion has been noticed. A decrease in power input to the feed pump is also witnessed.The results of the simulation study compared well to plant results available in the literature [14].

VI. CONCLUSIONS

Kalina cycle systems with single and double separators have been modelled and analyzed thermodynamically. The cycle efficiency and specific power are evaluated and the variation tendency is analyzed. It emerges that, for a given turbine inlet temperature, there exist an optimum ammonia mass fraction in the basic solution that yields maximum efficiency. The optimum ammonia mass fractions values for maximum efficiency and maximum power output are different. The double separator system yields higher vapor mass fraction compared to single separator system. The higher ammonia mass fraction at turbine inlet leads to lesser temperature after expansion. Also for separator temperature lesser than 110 ^{o} C and ammonia mass fraction in the basic solution higher than 0.6, higher ammonia mass fraction at turbine inlet leads to higher cycle efficiency. Improvements in the system design to the advantage of lower temperature after expansion more particularly prepare the system for next phase of testing.

VII. NOMENCLATURE

m = mass flow rate, kg/sec
T = temperature, ^{o} C
h = specific enthalpy, kJ/kg
Q = heat transfer, kW
W = work done, kW
x = ammonia mass fraction
F = vapor fraction
AP = approach point

VIII. ACRONYMS AND ABBREVIATIONS

HRSG = heat recovery steam generator
SEP = separator
SH = superheater
TUR = turbine
MXR = mixer
THR = throttle valve
COND = condenser
HE = Heat exchanger
DFLG = dephlegmator

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