Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2018, 5(9):154-159**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Low Power Organic Kalina Cycle Driven by Low-Grade Waste Heat

Ayad M. Salman

Energy and Renewable Energies Technology Center, University of Technology, Baghdad-Iraq

Abstract Kalina cycle is considered as one of the efficient power generation which can be used with the industrial processes associated with high heat rejected. Where, it is integrated with power generation plants as bottoming cycle. The current study presents computational investigation of using Kalina cycle Type of KCS34 as power generation cycle to convert the waste heat into useable electricity power. The thermodynamic analyses with optimization technique based on genetic algorithm have been conducted for Kalina cycle at various operating conditions. The results showed that the maximum cycle efficiency was about 29% at heat source temperature of 450 °C and inlet pressure of 100 bars. Moreover, the maximum second-law efficiency was about 60%. The results indicated the highlights advantages of using Kalina cycle for power generation applications from industrial waste heat.

Keywords Kalina cycle, waste heat recovery, low power

1. Introduction

Kalina cycle is considered as one efficient power generation instead of traditional steam Rankine system. Where, Kalina cycle can be used in combined power generation system as a bottoming system. In Kalina system, the aqueous-ammonia mixture is utilized as a working fluid. In thermal power generation plants, the thermal energy can be converted into useful energy as mechanical power to driver the generator and generate electricity. In these systems, the heat is transferred from high temperature sources and rejected through low temperature heat sink.

The organic Rankine cycle (ORC) and Kalina cycle can deliver a good solution for the concerns about the recovering the low-temperature heat sources which is used for heat recovery associated with industrial processes. ORC system is a steam Rankine cycle where the organic fluids such as a refrigerants and hydrocarbons are utilized instead of steam. In many ways, ORC system has been used to recover the energy from low-temperature heat sources (LTHS) like waste heat, solar and geothermal energies applications [1-6].Water-ammonia as a binary fluid was used in Kalina cycle in order to optimize the system in terms of wide ranges of the operating conditions in low-temperature of the waste heat recovery [7-10].

The management of the recover heat from the fluid flow through industrial processes is the major problem that faced the heat recovery process due to the most equipment that used in industrial systems are closed system [7]. Moreover, energy and economic investigations on Kalina cycle have been carried out in order to reveal the core and direction of the enhancements of its performance [11, 12].

There are several configurations for Kalina cycle like KCS11, KCS1-2 and KCS34g driven by low-temperature and various applications were summarized in [13].Obtaining high performance for Kalina system requires high pressure. Therefore, comparison with ORC system has been made based on Kalina cycle type of KSC11 which showed a better overall performance at low-temperature and moderate pressure for geothermal applications [14]. The combination of the ORC system and Kalina cycle for high heat transfer efficiency with low heat loss into heat-sink provides that Kalina cycle has higher efficiency compared with ORC system at the same operating temperature ranges [15]. However, for low power capacity applications at medium-heat source temperature,

Kalina cycle seems not to be acceptable due to a little improvement in the performance compared with ORC system when the operating conditions and components areas have been optimized [16].
The current work aims to evaluate the performance of Kalina cycle which can be used with low-medium heat source from industrial waste heat for power generation purposes. Moreover, the determining the optimum operating conditions are offered in the current study. Where, the main objective is thermodynamic analysis of Kalina cycle at various operating conditions in terms of inlet pressure/temperature and mass fraction of the working fluid. In order to achieve this target, EES code (Engineering Equation solver) has been developed to carry out the thermodynamic analysis.

2. Kalina Cycle Layout

The proposed Kalina cycle is based on the simple configuration which is called KCS34 as shown in Figure (1). The simple Kalina cycle consists from: expander, generator, low and high temperature recuperator, evaporator, condenser, separator, pump, throttling valve and mixer. The superheated vapor of the working (mixture of ammonia-water) expands through the expander stage and then mixed by the mixer with the ammonia liquid coming from the separator. The working fluid leaving the mixer is named the basic solution. Where, the working fluid is rich ammonia vapor. The working fluid in the condenser is lower ammonia mass fraction. Then the working fluid passes into condenser and pump which is pumped into evaporator.

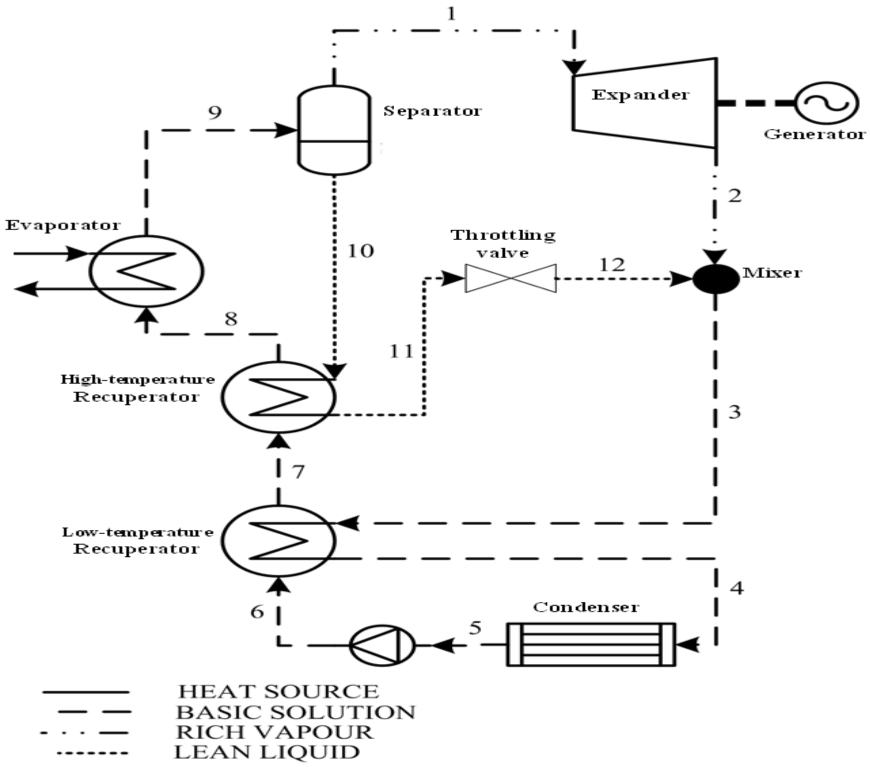

Figure 1: Layout of Kalina cycle type of KCS34

3. Modelling of Kalina Cycle

The following equations can be used for different Kalina cycle components' a below:
The power output generated by the turbine is obtained by:

$$W_{Exp} = \dot{m}(h_1 - h_2) \quad (1)$$

The power through the generator is determined by:

$$W_{Gen} = \eta_{Mech}\eta_{Gen}W_{Exp} \quad (2)$$

The heat transfer through high-temperature recuperator is calculated as:

$$\dot{m}(h_8 - h_7) = \dot{m}(h_{10} - h_{11}) \quad (3)$$

The heat transfer through low-temperature recuperator is calculated as:

$\dot{m}(h_7 - h_6) = \dot{m}(h_3 - h_4)$ (4)

The heat rejected through the condenser is calculated as following:

$Q_{Cond} = \dot{m}(h_4 - h_5) = \dot{m}_W C_{P_W}(T_{W_{out}} - T_{W_{in}})$ (5)

The heat balance through the mixer is as following:

$\dot{m}h_2 + \dot{m}h_{12} = \dot{m}h_3$ (6)

The heat balance for the separator is as following:

$\dot{m}h_9 = \dot{m}h_1 + \dot{m}h_{10}$ (7)

Throttling process though the throat valve is:

$h_{11} = h_{12}$ (8)

The power consumption by the pump is calculated as:

$W_{Pump} = \dot{m}(h_6 - h_5)$ (9)

where W_{Exp} represents the power output, W_{Gen} is the electrical power from the generator, W_{Pump} is the power consumption by the pump, h is the specific enthalpy, $\dot{m}$ is the mass flow rate of the working fluid, Q_{Cond} is the heat rejected through the condenser, C_{P_W} is the water specific heat, T is the temperature, η_{Mech} and η_{Gen} are the mechanical and generator efficiencies. The sub-script W refers to water.

The isentropic efficiencies of the expander and pump are calculated as following:

$\eta_{Exp} = \Delta h_{actual} / \Delta h_{isentropic}$ (10)

$\eta_{Pump} = \Delta h_{isentropic} / \Delta h_{actual}$ (11)

Table 1: Input parameters for Kalina cycle modelling code

Parameters	Values/ranges
Expander inlet temperature (K)	750
Expander isentropic efficiency %	80
Generator efficiency %	90
Minimum pinch point temperature difference for recuperator (K)	8
Minimum pinch point temperature difference for condenser (K)	4
Minimum vapor quality at separator inlet %	5
Minimum vapor quality at expander outlet %	90
Temperature difference of the cooling water (K)	8
Water temperature at condenser inlet (K)	293

4. Optimization

The optimization aims to maximize the Kalina cycle efficiency for the designed power out from the system in terms of net power output as following:

$\Phi = max\left(\frac{W_{net}}{Q_{added}}\right)$ (12)

where Φ is objective function, W_{net} is the net power output and Q_{added} is the heat added to power the system.

The optimization algorithm includes: the objective function, design constraints, values/ranges of input parameters and decision variables. The objective function is the cycle efficiency. The optimization process based on genetic algorithm (GA) is carried out to maximize the cycle efficiency.

5. Results and discussion

Figure (2) shows the effect of the mass fraction of the ammonia on the Kalina cycle efficiency various pressure at the expander inlet. It can be found that the maximum cycle efficiency was about 29.5% at mass fraction of 0.76 and inlet pressure of 100 bars. The lowest cycle efficiency was of 26% at mass fraction of 0.77 and inlet pressure of 60 bars. The maximum inlet pressure was ranged between 60 bars and 100 bars in order to avoid operating the system under critical conditions.

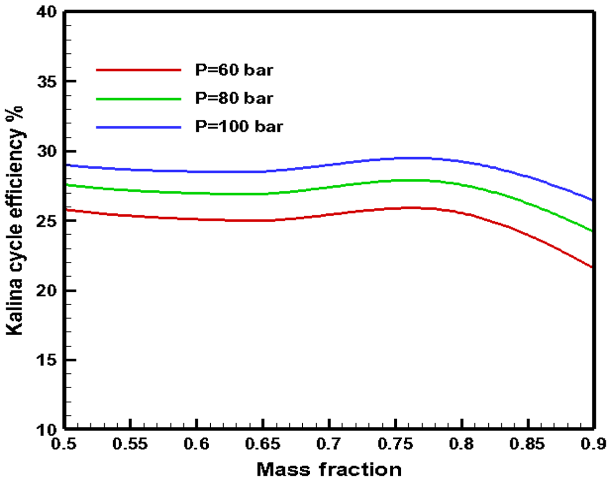

Figure 2: Effect of ammonia mass fraction on Kalina cycle efficiency for different pressure at expander inlet

Figure 3 shows the effect of source temperature on the Kalina cycle efficiency at ranges of heat sink temperature between 10 and 25 °C. The maximum cycle efficiency was obtained at sink temperature of 10 °C due to increase the difference between the source and sink temperature. While the minimum cycle efficiency was about 27% at sink temperature of 25 °C due to decrease the difference between the heat sources and sink temperatures.

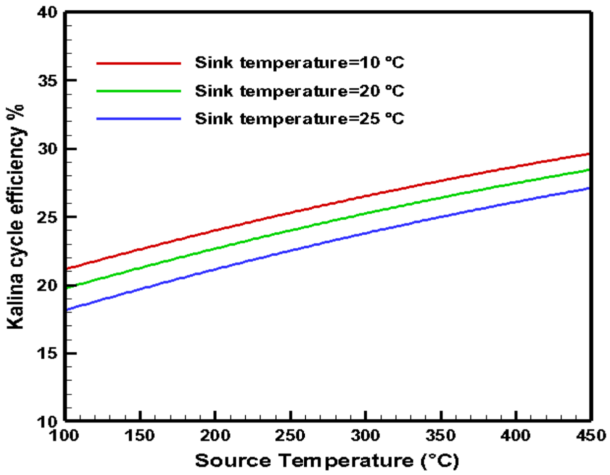

Figure 3: Effect of source temperature on the Kalina cycle efficiency at three different sink temperature

Figure (4) shows the effect of ammonia concentration of the Kalina cycle at various inlet expander pressures with heat sink temperature of 25 °C. The minimum cycle efficiency of about 25% inlet pressure of 60 bars at expander inlet was obtained.

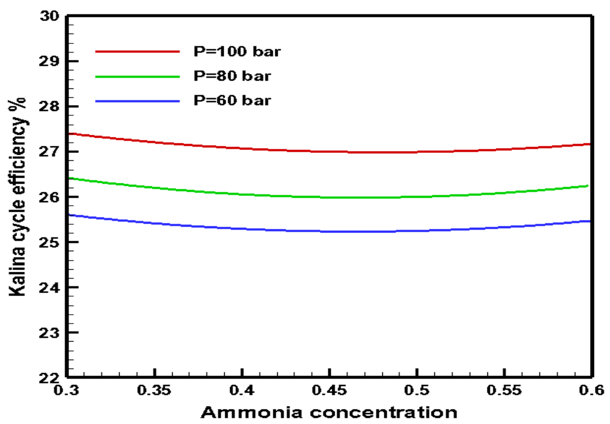

Figure 4: Effect of ammonia concentration on Kalina cycle at different expander inlet pressure

Figure (5) shows the effect of source temperature on the second-law efficiency of the Kalina cycle. It can be found that the maximum second-law efficiency was about 60% at inlet temperature of 450 °C with inlet expander pressure of 100 bars.

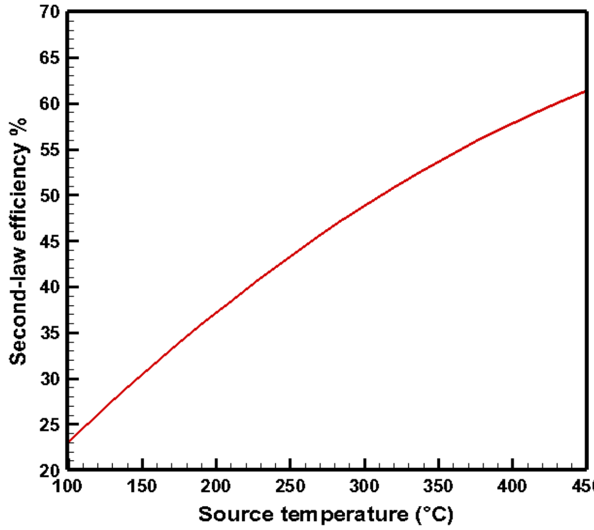

Figure 5: Effect of source temperature on the second-law efficiency

6. Conclusions

A computational effort based on the Kalina cycle methodology is presented for medium temperature applications such waste heat recovery. The genetic optimization algorithm was applied in order to maximize at specified operating conditions.

The obtained results from the Kalina cycle analysis based thermodynamic analysis and optimization showed that the Kalina cycle performance in terms of efficiency has been affected by the operating conditions namely: heat source temperature, heat sink temperature and expander inlet pressure. The ammonia concentration as a working fluid has clearly effect on the Kalina cycle efficiency. Based on the current results, the Kalina cycle has advantage to generate power from medium-temperature moreover it can be combined as bottoming cycle with organic cycle and gas turbine cycle which operates at high temperature.

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