High-efficiency thermodynamic cycles for Kalina power generation systems: A comprehensive review

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Abstract: In this paper, different Kalina power cycles have been identified and presented. The main endeavor of this review paper is to propel a complete understanding of simple and complex Kalina power generation systems. Additionally present status emphasizing some enhanced performance in Kalina power systems has been detailed. A hypothetical study of diverse Kalina power systems, incorporating an ejector, distillation column, sliding condensation, split cycle, double pressure and variable composition has been made. These modifications to the fundamental cycle decrease expansion losses using diverse principles and they require dissimilar mechanical hardware of special intricacies and expenditures. Kalina cycle with an ejector has maximum potential for efficiency improvement followed by the sliding condensation pressure method. Generally, the alternative options present several benefits to Kalina power systems such as decreased losses, improved performance and reduced energy expenditure.

1. Introduction
It is vital to reduce fossil fuel consumption and greenhouse gas emissions for a sustainable future. Organic Rankine and Kalina power systems are two promising options which use low grade energy and have been extensively discussed in the available literature. The striking characteristic of the Kalina cycle is the increase in efficiency due to heat exchange processes occurring at varying temperatures. The increase results due to higher net work output. Efficiency is augmented by means of recuperator exchangers. The increase occurs as a consequence of the distinctive variable boiling and condensing feature of the work medium. The heat addition and rejection to the ammonia–water mixture takes place at varying temperatures. The varying temperature through the heat-exchange processes decreases the thermal unavailability. Moreover thermal pinch in a boiler is also reduced. Scientists and engineers have been investigating for the performance optimization of Kalina cycle. Researchers are making ever increasing efforts to compute thermodynamic properties of ammonia-water mixture precisely and analyze diverse Kalina cycles to improve thermal and exergy efficiencies.

2. Kalina cycle with a distillation column
Performance of the Kalina power cycle can be improved by using a distillation column. The DCSS configuration comprises of a flash separator, a flash preheater, two reheaters, an absorber, a feedwater heater and a condenser. The working fluid exiting from the turbine (15) is refrigerated in the flash preheater (16) and in the reheaters (18). It is mixed with a poor ammonia mixture (6) approaching from the separator so as to obtain a lower concentration of ammonia and hence a higher boiling temperature. This concentration (19) is called the basic composition.

After being condensed in the condenser (20) the mixture is pumped (21) to the second reheater (22) and heated. A portion of the liquid is extracted (23) to weaken the ammonia-rich stream (8) entering the separator so as to refurbish the composition of mixture (9). The remaining mixture (24) is exchanges heat in both first reheater (1) and flash preheater (2). The stream is divided into a liquid stream (3) with a low ammonia fraction and a vapor stream (7) with a high ammonia fraction in the flash
separator. The temperature of both the streams reduces while heat is exchanged in the first reheater and the second reheater (5). After throttling the stream (6) is then mixed with the incoming stream from the turbine. The liquid (23) is mixed with the vapor stream (8) in order to refurbish the composition of the working fluid. Next the mixture (9) is cooled (10) in the feedwater heater, condensed (11) in the condenser and pumped (12) again to the feedwater heater (13) before entering the vapor generator.

Fig. 1. Layout of Kalina power system with a distillation column [1]

Glasare et al. [1] investigated and compared three dissimilar arrangements of the Kalina bottoming cycle by changing the diverse compositions in the cycles. The cycle energy efficiency and the second law efficiency have also been calculated. In addition to the rate of exergy loss in each unit was also computed. However the three configurations differ very little in efficiency as depicted in the results. This configuration is a novel alternative to the arrangement investigated by Chuang and Ishida [2] and temperature pinches in the heat exchanger are less intense in comparison to the original cycle described by El-Sayed and Tribus[3]. Chuang and Ishida observed that a distillation column reduces the intensity for pinch points because the maximum pinch was established in reheater 1.

The energy and exergy efficiencies differ with the working and the basic compositions. The maximum value of energy and exergy efficiencies are found at a concentration of 0.645 kgNH₃/kg,tot. The exergy efficiency is 34.10% and the exergy efficiency is 69.19% at this optimum composition.

3. Kalina cycle with sliding condensation pressure
The efficiency of the KSG-1 cycle can be improved by utilising the sliding condensation pressure technique for low grade waste energy obtained from industry. The layout is shown in Fig. 2. The operating medium is a mixture of ammonia-water. The functioning of the system is detailed as follows. The saturated liquid at state 1 is pumped from the tank into the recuperator. The subcooled liquid at state 2 is
heated to state 3 by the recuperator. Next, the basic solution extracts heat from the brine solution in the evaporator and passes it to the separator at state 4. The basic solution cannot be completely vaporized since the heat source is brine at 120°C and hence a separator is utilized to split the two-phase fluid into a rich ammonia mixture of state 5 and a lean ammonia mixture of state 6. The expansion pressure ratio in the turbine can be adjusted using sliding pressure control method whilst the vapor mixture is changed to state 7. Alternatively, the liquid mixture is throttled through the expansion valve to state 8. The exhaust gas from the turbine is mixed with the low-pressure liquid in the mixer. Subsequently the mixture is passed to the recuperator where it rejects heat to the saturated liquid coming from the tank. Next this mixture is condensed in the air-cooled condenser and converted again to saturated liquid.

Wang et al. [4] established a hypothetical model based on sliding condensation pressure method and subsequently framed a mathematical program to investigate the cycle performance. The condensation pressure alteration according to the varying ambient temperature has been mathematically confirmed with different ammonia-water mixture concentrations. Hu et al. [5] investigated the off-design performances of an organic Rankine cycle system with three diverse control techniques together with sliding pressure control. Generally, sliding pressure control is used to cater to the changeable demand in load by varying evaporation pressure. Modi et al. [6] and Li et al. [7] performed an off-design performance analysis of the Kalina cycle with sliding pressure control. Usman et al. [8] carried out experimental analysis of an organic Rankine cycle using sliding pressure control method. In comparison to the ORC with a clean working fluid, a zeotropic working fluid like an ammonia-water mixture is used in the Kalina cycle. This provides flexibility as far as the ammonia mass fraction is concerned.

Fig. 2. Layout of the Kalina power system with sliding condensation pressure [4]

4. Kalina split-cycle power system
The effectiveness of Kalina power system could be also enhanced by using split system. Fig. 3 is the schematic representation of the Split-cycle method. To concentrate on the unique split stream boiler, the Split-cycle arrangement was configured with fewer components required for evaluating the concept. Two streams a rich stream (25) and a lean stream (31) enter the boiler. The rich stream is completely vaporized before it mixes with the lean stream in the mixer (4) heated to its boiling point. This configuration helps in
lowering the temperatures as liquid (25, 31) is converted to vapor (2). An auxiliary mixing subsystem is necessary to generate the two streams with required concentrations and mass flow rates. This comprises of 3 splitters and 2 mixers and the 3 splitters split the incoming streams (11, 12 and 18) as desired. In most cases, desired flow rates and concentrations of the streams can be achieved from a series of splitting fractions, however there may be situations when streams cannot be formed as needed. The slope of the evaporation temperature curve can be attuned to the temperature gradient of the heating source by choosing an optimum composition for both streams, as shown in Fig. 3.

Fig.3. Schematic representation of Kalina split system [9]

Larsen et al. [9], concluded that the components that produce maximum impact on process efficiency are separator, recuperator, boiler and turbine. Additionally, it was suggested that the most significant variables that affect the performance of the system were the concentration of ammonia and temperature of the cooling water.

Moreover an economic study of the Kalina split-cycle was also conducted and it was concluded that payback time of this configuration is comparable to that of a conventional Kalina cycle. The maximum thermal efficiency is 23.2% with reheating option which was about 3.4-5.9% more in comparison to the reference cycle. The maximum thermal efficiency was obtained as a result of optimization performed using the genetic algorithm technique. Nguyen et al. [10] devised a technique to optimize this unique Kalina system and confirmed that in comparison to a typical Kalina power system the split cycle process enhances the thermal efficiency from 20.1% to 21.5%. Nevertheless this optimization technique is confined to the boiler and turbine components only. Bombarda et al. [11] thermodynamically compared the performance of Kalina cycle with that of an ORC cycle, with hexamethyldisiloxane working fluid. The waste heat was recovered from two Diesel engines both with a power of 8900 kW. Assuming a LMTD of 50°C for heat exchanger, an electric power of 1615 kilowatts in the Kalina cycle and 1603 kilowatts for the ORC cycle was estimated. Marston [12] theoretically investigated the Kalina cycle by varying
different parameters. The turbine inlet composition and separator temperature were recognized as the significant variables for optimization. These results were acknowledged by Nag and Gupta [13], who conducted an exergetic study of the Kalina cycle, and confirmed that the turbine inlet temperature and composition, in addition to the separator temperature, as producing the maximum effect on the thermal efficiency of the system. Dubey et al. [14] critically investigated a CO₂/propylene based transcritical cascaded system for simultaneous cooling and heating. Energy utilization factor (EUF) enhancement of 8% was confirmed by the addition of a split unit. A multilinear regression analysis was carried out for the transcritical cascaded refrigeration system to optimize EUF, intermediate temperature and mass flow ratio.

5. Double pressure Kalina power system

Yet another method to improve the performance of Kalina cycle is the use of a double pressure system as shown in Fig.4. A cycle’s stream (17) absorbs some heat from the heat source and leaves the LP evaporator as it is a two-phase mixture with both liquid and vapor (1). Hence the phases can be divided in separator 1, from where the ammonia rich stream passes to the turbine (4) after further heating in the HT regenerator. The residual liquid stream (3) with lower concentration of ammonia is pumped to the HP evaporator where it absorbs heat. The two phases are again divided in separator 2, from where the ammonia rich stream passes to the turbine (12). The lean stream then enters the pressure valve (8) via the HT and LT regenerator. The stream’s pressure drops and it mixes with the exhaust of the turbine (14) in the mixer (14). The product of the mixer (10) condenses in the condenser. The condensate (15) is then pumped (6) to be preheated by the separator’s mentioned liquid extract and enters the LP evaporator (17) via the economizer.

Rasool et al. [15] conducted an optimization study for four different arrangements of double pressure Kalina cycle system all of which are innovations of Kalina cycle system 11. Exergy efficiency is considered as the objective function and the modified double pressure cycles were compared to the base Kalina cycle. Findings illustrate that the Kalina cycle system 112b has the maximum efficiency at the base condition. It was further demonstrated that exergy efficiency and the cost of equipment rose by escalating
the heat source temperature at the optimum condition however the payback cost of electricity decreases. Marson and Hyre performed a comparative analysis of single stage and triple stage Kalina cycle with a triple pressure steam cycle [16]. Sadeghi et al. [17] projected a modified Kalina cycle with two turbines which may be synchronized appropriately with a heat source operating in a range of 80–200°C. Guo et al. compared the base Kalina cycle [18] with a double pressure evaporation arrangement. The results confirmed that the novel arrangement increased the efficiency of the base cycle by 17 percent.

6. Kalina cycle with ejector
In an EKalina cycle expansion energy is recovered and fluid pressure is increased by replacing the throttle valve and the absorber with an ejector. The main components of an EKalina cycle include a regenerator, vapor-liquid separator, expander, evaporator, condenser, fluid pump and an ejector. The Ammonia solution leaving the evaporator is divided into saturated rich vapor and saturated weak liquid in the separator. The saturated vapor flows to the expander while the saturated liquid flows to the ejector via the regenerator. The exhaust from the expander mixes with the cooled liquid coming out from the regenerator. Further the mixture coming out from the ejector is condensed in the condenser and pressurized back to the evaporator after absorbing heat in the regenerator.

Li et al. [19] projected a Kalina cycle with ejector as a replacement for the throttle valve and the absorber. The back pressure of the expander is reduced by the ejector thus escalating the power produced as well as thermodynamic efficiency of the cycle. For values of $X_B$ in the range of 0.5-0.9, $X_V$ of 0.92-0.98 and water temperature of 110°C, the maximum and minimum improvement in power of the EKalina cycle in comparison to KCS 11 are 39.55%, and 0.75% respectively. The increases in efficiency are 39.13%, and 0.72% respectively. Rashidi et al. [20] introduced an ejector before the evaporator in a novel configuration of Kalina combined power and cooling cycle. It was concluded during investigation of energy efficiency that under similar operating conditions the novel cycle with an ejector provides a performance enhancement without significantly increasing system intricacy.

Seckin et al. [21] suggested an arrangement of a cogeneration cycle wherein an ejector cooling system is combined with the Kalina power system to recuperate heat from weak ammonia mixture which exits from the separator at an elevated temperature and pressure and is discharged as a waste. The thermal efficiency of the cogeneration cycle augmented with rise in strength of weak NH$_3$-H$_2$O solution. However the efficiency reduced with both increasing condenser exit temperature and pressure of heat recuperator. Thermodynamic modeling and simulation of the novel cogeneration cycle was performed with the

![Fig.5. Layout of the Kalina cycle system with ejector [19]](image-url)
viewpoint of the energy and exergy. The exhaust of the turbine was separated in two streams one to feed the condenser and the other to feed flow heater. Dubey et al. [22] suggested a numerical model for investigating the performance of a CO2/propylene based transcritical cascade refrigeration-heat pump system. The expansion valve was replaced by a vortex tube for recuperating expansion work. An improvement of 6% in the COP of the suggested system was calculated for the specified values of temperatures and pressures.

7. Composition-adjustable Kalina cycle
Another option to reduce the expansion losses is the use of separators which have potential for improving efficiency. As shown in Fig. 6, the basic solution a saturated liquid flows to Tank 1. A density sensor is positioned at its exit to determine the density of the working fluid to calculate its composition and sent as a feedback signal for monitoring the composition. The solution at state 3 is pressurized and converted to subcooled liquid. This subcooled liquid absorbs heat in the recuperator and is then heated further in the evaporator to convert into a two-phase mixture by geothermal brine. The temperature of the brine water is set as 120°C in this study so that operating variables are similar to that in literature [25] for ease of comparison.

The basic solution is not fully converted into vapor due to lower temperature of brine. Therefore a separator is used to split the two phase mixture into a rich stream of saturated vapor and a lean stream of saturated liquid. The high temperature high pressure vapor mixture expands in the turbine to produce useful work. The low pressure liquid at state 10 is mixed with the low temperature low pressure exhaust from the turbine in a mixer. This two-phase mixture then passes to the heat exchanger, where the temperature of this mixture reduces again after losing its heat to the basic solution from pump1. The ammonia-water mixture from the recuperator is split into two streams in a separator to facilitate the condensation process. The incoming liquid stream from Tank 2 is subsequently pumped and subsequently sprayed in Mixer 2, condensing the concentrated ammonia vapor stream further. The mixture exchanges heat from the atmospheric air and is converted into saturated liquid at state 1.

Fig.6. Configuration of Variable Composition Kalina cycle [23]
Wang et al. [23] proposed a numerical model to simulate the operating code of a variable composition Kalina power system. A mathematical program is subsequently designed to investigate the performance of the cycle with changing climatic conditions. It was established that better thermal efficiency could be attained by adjusting the composition of Kalina power system in comparison to a conventional system. Although, such an increase in thermal efficiency essentially depends on the system variables and climatic conditions. The thermal efficiency of Cycle B is steady at 6.12%. Nevertheless, the thermal efficiency of the other cycle A augmented from 6.12% to 9.24% with decrease in ambient temperature. The ambient air temperature can be synchronized with the condensation temperature of working fluid to increase the power output of the turbine considerably.

Hua et al. [24] examined the transient performance of a Kalina cycle for high-temperature waste heat recuperation, which can control the concentration of the working fluid. This method controls the on/off state of two valves to maximize power generation with varying temperature of the waste heat source. The inlet pressure of the turbine is altered by regulating the concentration of the working fluid. With a variation of flow rate ranging between With a variation of flow rate in the range of 100% to 80%, the Kalina power system efficiency by means of concentration control is 12.8% more in comparison to valve throttling method. A thermal efficiency of 21.25% was established for this cycle.

Nasruddin et al. [25] numerically investigated a KCS-34 Kalina cycle with Cycle Tempo 5.0 software and validated the results with the experimental data of the Husavik power plant which presented a good agreement. Hettiarachchi et al. [26] investigated the efficiency of KCS-11 power system for harnessing renewable geothermal energy. An optimum value for ammonia concentration was established for a given turbine inlet pressure. Sun et al. [27] investigated the performance of a KCS-11 Kalina cycle for research in solar energy. It was confirmed that the ammonia mass fraction was a significant system variable and its optimization would decrease irreversibility of the system.

8. Conclusions
Extensive reviews of Kalina Power cycle modifications such as use of a distillation column, sliding condensation pressure, split unit, ejector, double pressure and composition variation have been carried out in the paper. The below mentioned conclusions can be drawn from the above review.

• Configuration with a distillation column in the DCSS reduces efficiency due to higher exergy losses in the DCSS owing to reduced heat transfer. However there is an advantage that temperature profiles are smooth which are achievable with counter current heat transfer. Moreover an improved design of the distillation column would attain additional exergy efficient heat transfer.

• The estimated thermal efficiency of the Kalina cycle by sliding condensation pressure is 8.21%, enhanced by 33.5% in comparison to the conventional Kalina cycle.

• An average thermal efficiency of 23.2% can be attained by split cycle while utilizing reheat in contrast to 20.8% without reheat. Reheat augments the thermal efficiency of conventional cycle by 3.4-5.9%.

• Maximum improvements in the exergy efficiencies of double pressure cycle as compared to the conventional cycle are 16.7, 23.6 and 10.2 % for the 3 temperature levels, 383.15 K, 413.15 K and 443.15 K, respectively.

• For values of X_B in the range of 0.5-0.9, X_V of 0.92-0.98 and water temperature of 110°C, the maximum and minimum improvement in net power output of the EKalina cycle in contrast to KCS 11 are 39.55%, and 0.75% respectively. The increases in efficiency are 39.13%, and 0.72% respectively.

• With a variation of flow rate in the range of 100% to 80%, the Kalina power system efficiency by means of concentration control is 12.8% more in comparison to valve throttling method. A thermal efficiency of 21.25% was established for this cycle.
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