Thermodynamic Evaluation of a Solar Based Kalina Cycle

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Abstract

Solar energy has enormous potential in the world. It can produce energy generation several times larger than the overall world energy demand. However, a major challenge to implement it is the high costs of electricity generation from solar sources. These costs can be reduced by improving the conversion efficiency from solar energy to electrical energy. Currently, the Rankine cycle is the most frequently used power cycle for generating electricity from solar energy. An interesting alternative to the commonly used Rankine cycle that uses solar heat energy as its input is the Kalina cycle. The Kalina cycle uses a mixture of ammonia and water as its working fluid. When using a mixture of ammonia and water as a working fluid, temperature varies while heat is added and rejected during phase change. This theoretically would be more efficient than a power cycle who only uses water as its working fluid. This paper examines the performance of a Kalina cycle with solar energy from concentrating solar plant as the input heat. A solution algorithm is developed and programmed to evaluate the thermodynamic properties of a Kalina cycle with inlet turbine temperature of 400 °C. Parametric analysis was done to study the effects of turbine inlet pressure and turbine inlet ammonia concentration on cycle efficiency. Results shows that both parameters have a positive relationship with cycle efficiency. Turbine outlet pressure was found to be a major influence on cycle efficiency. Maximum efficiency was found to be 33% at a turbine inlet pressure of 140 bar and turbine inlet ammonia concentration of 0.8.

Keywords
Kalina Cycle, Solar energy, Efficiency, Recuperator, Evaporator

1. Introduction
The consumption and generation of electricity will continue to increase to fulfil energy demands globally. This is also the case for Malaysia. Gan and Li (2008) have projected that Malaysia's energy consumption and carbon emissions will triple by 2030. This growing demand presents a challenge on how to optimize available resources for generation of electrical power. Instead of relying of fossil fuels, generation of electricity renewable energy sources such as solar energy provides should instead be prioritized. Generating electricity using renewable resources such as solar energy is an attractive option to reduce the heavy reliance placed on fossil fuels. Research on solar technologies such as concentrating solar power (CSP) has shown rapid amount of growth in recent years. The most applicable usage for CSP in Malaysia is the parabolic trough collector type (Islam et al. 2019). However, due to lack of wide scale application, plants running on solar energy is currently more expensive to initially implement and has a higher overall levelized cost of electricity (LCOE) compared to fossil fuels. Efficiency is a major factor in determining LCOE. Therefore, solar energy plants should strive to increase efficiency to compete with fossil fuel plants in the economic department (Sütterlin and Siegrist 2017; Jaćimović et al. 2020).

The conventional Rankine cycle used for power generation could be improved. The Kalina cycle presents a particularly attractive option (Takeshita et al. 2005). The usage of an ammonia-water mixture as its working fluid is more thermally efficient as heat addition and rejection occurs at varying temperature during phase change (Gan and Li 2008; Islam et al. 2019; Kalina and Leibowitz 1987). Hence, by replacing the Rankine cycle with a Kalina cycle, a better utilization of resources can be achieved (Zhang et al. 2012). This study aims to evaluate the thermodynamic performance of a Kalina cycle with KC-12 layout for a turbine inlet temperature of 400 °C. The objective is to perform parametric analysis and optimization to obtain maximum thermal cycle efficiency. A solution algorithm is to be programmed using MATLAB to solve the Kalina cycle. Genetic algorithm is used for optimization purposes.

1.1 Objectives

The main aim of this research is to model a Kalina cycle fueled with solar source. The specific research objectives to achieve the above aim of this research work are as follows:

i) To evaluate the thermodynamic performance of the Kalina cycle at different turbine inlet pressures and ammonia mass concentration.
ii) To optimize the efficiency of the Kalina cycle.

2. Literature review

In 1984, an alternative to the conventionally used Rankine cycle called the Kalina Cycle was introduced (Silvestri 1985). Invented by Dr. Alexander Kalina, it was initially introduced to be utilized as a bottoming cycle for combined cycle power plants. The difference between a conventional Rankine cycle and Kalina cycle is its working fluid. Instead of using a pure component such as water as its working fluid, the Kalina cycle uses a multi-component working fluid. With that said, in many case studies pertaining to Kalina Cycle, a mixture of ammonia and water is often used as the working fluid. The Kalina Cycle can also be described as a combination between a Rankine Power Cycle and an ammonia absorption refrigeration cycle. Since its introduction, the Kalina cycle is considered as an ambitious competitor to the Organic Rankine Cycle and presents the most significant improvement in thermal power plant design since the introduction of the Rankine cycle in the mid-1800s (Zhang et al. 2012).

Theoretically, a Kalina cycle is more efficient than a Rankine cycle. As the Kalina cycle uses a mixture, the heat addition and rejection will occur at varying temperatures during phase change. the Kalina cycle could achieve a thermal efficiency of 45% compared with about 33% for a conventional Rankine cycle. A comprehensive analysis on the system design of the Kalina cycle and its technological progress was presented by Kalina and Leibowitz (1987). The cycle components were compared with currently used equipment for a standard steam Rankine cycle. A cost analysis was showcased on the components needed for both the Kalina and the steam Rankine cycle. The initial purchasing cost for the Kalina cycle was slightly greater but the increase in power generation would undoubtedly compensate this costs over the plant life cycle (Kalina et al. 2015).

There has been little experimental research done on the Kalina cycle. Those that had been done were all centred on low temperature applications. An experiment by Takeshita et al. (2005) shows that an ammonia-water power cycle would require less heat input than a Rankine cycle for a similar output. Studies on high temperature Kalina cycle applications in the range of 350-500°C indicates possible thermodynamic benefits. A research by Ibrahim and Kovach (1993) analysed the impacts of various ammonia mass fraction and separator temperature on thermodynamic efficiency of a Kalina bottoming cycle powered by gas turbine exhaust. Results obtained shows a 10-20% increase in efficiency compared to the Rankine cycle with identical boundary conditions. Furthermore, the Kalina cycle was found to be more efficient than a triple-pressure steam cycle when used as a gas turbine bottoming cycle. Singh and Kaushik (2013) showcased the energy analysis of a Kalina cycle coupled with a coal-fired steam power plant, where a maximum cycle efficiency was found at a turbine inlet pressure of 40 bar and an ammonia mass fraction of 0.8 at the turbine inlet.

Kalina cycles driven by solar energy has been the subject of several research studies (Modi and Haglind 2014). Knudsen et al. (2014) discovered that a Kalina cycle with direct steam generation at a turbine input temperature of 450°C has a slightly lower exergy efficiency compared with a regular Rankine cycle. However, the Kalina cycle has the potential to operate at a lower cost due to its ability to be operated at higher turbine inlet pressures. For Concentrating Solar Power plants where the temperature is above 500 °C, the Kalina cycle is found to not be beneficial enough as the Rankine cycle present a better economic option (Modi and Haglind 2015).

3. Methodology

The Kalina cycle layout KC-12 as shown in Figure 1 was chosen to be evaluated. KC-12 was chosen as it is most suitable for turbine inlet temperatures of around 400 °C and works well with solar energy (Modi et al. 2016; Nag and Gupta 1998). Taking into consideration the DNI received and general weather conditions in Malaysia, this temperature can be readily achieved through concentrating solar power technologies.

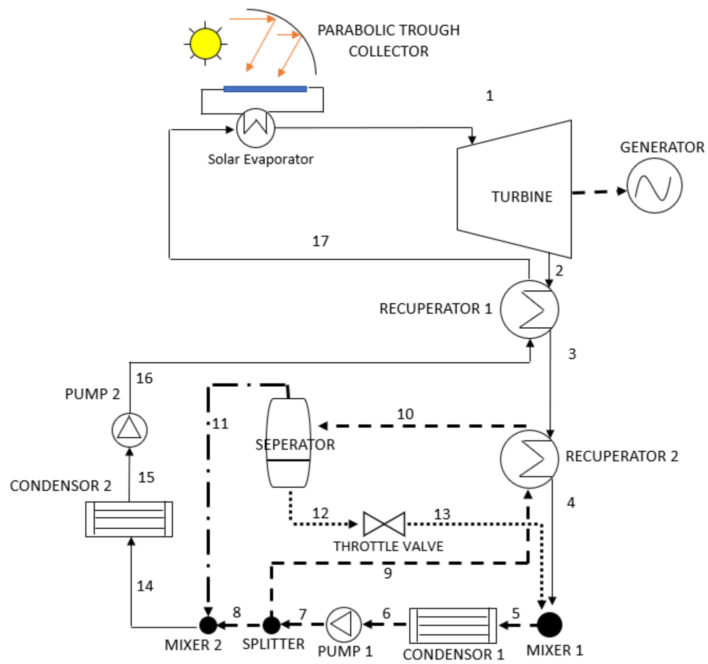

Figure 1. The Kalina cycle KC-12 layout [adapted from (Modi et al. 2016)]

For ease of analysis, several assumptions were made. First, the cycle is assumed to be in a steady state operation. Next, kinetic energy and potential energy changes in the devices are neglected. The working fluid exiting the condenser is assumed to be a saturated liquid. Furthermore, the working fluid entering the turbine is a saturated vapor. Pressure drops in both condensers are neglected. Devices are assumed to be adiabatic and heat losses in pipes are neglected.

Available literature shows that turbines generally operate with an isentropic efficiency between 79% and 90% (Eva Thorin 2000). Smaller turbines with few MW generations of electricity tend to have lower isentropic efficiency. With that in mind, a suitable value of 82% is assumed for this study. For pumps, typically the isentropic efficiency ranges between 60% to 85% (Nag and Gupta 1998). Hence, a reasonable value of 75% was considered for this study. Furthermore, to ensure two-phase flow at separator inlet, the minimum vapor quality required at the inlet is set to 5%. To avoid corrosion of blades due to cavitation at turbine outlet, the minimum vapor quality at the turbine outlet is set at 90%. This is above the recommended 88% value required for realistic results and practicality purposes (Ganjehkaviri et al. 2015). Fixed input parameters for the Kalina cycle are as shown in Table 1.

Table 1. Fixed input parameters for the Kalina cycle

Description	Unit	Value
Turbine inlet temperature, T_1	°C	400
Turbine mechanical efficiency, $\eta_{tur,m}$	-	98%
Generator Efficiency, η_{Gen}	-	98%
Turbine isentropic efficiency, $\eta_{is,tur}$	-	82%
Pump isentropic efficiency, $\eta_{is,pump}$	-	75%
Minimum turbine vapor quality, X_2	-	0.90

Mass-energy balances is applied to the separator, mixers, and splitter to obtain the mass flow rate at various point in the system shown in figure as suggested by (Marston 1990). The energy equations of the devices are as shown below are used to find the properties at different states of the Kalina cycle and to calculate the system efficiency.

$$\dot{W}_{\mathrm{Tur}} = \dot{m}_1 \cdot (h_1 - h_2) \tag{1}$$

$$\dot{W}_{\mathrm{pu1}} = \dot{m}_6 \cdot (h_7 - h_6) \tag{2}$$

$$\dot{W}_{\mathrm{pu2}} = \dot{m}_{15} \cdot (h_{16} - h_{15}) \tag{3}$$

$$\dot{W}_{Gen} = \dot{W}_{Tur} \cdot \eta_{tur,m} \cdot \eta_{Gen} \tag{4}$$

$$\dot{W}_{net} = \dot{W}_{Gen} - \dot{W}_{pu1} - \dot{W}_{pu2} \tag{5}$$

$$\dot{Q}_{in} = \dot{m}_1 \cdot (h_1 - h_{10}) \tag{6}$$

This solution is then programmed into MATLAB. To obtain the thermodynamic properties of the ammonia-water mixture, REFPROP was used. The mixing parameter chosen was the default Tillner-Roth and Friend equation. For optimization purposes, the decision variables are the turbine outlet pressure, separator inlet temperature and separator inlet ammonia mass fraction. Range of turbine pressure is limited to between 4-6 bar. Ammonia concentration at separator inlet is between 0.45 to 0.55. Meanwhile, the separator inlet temperature is fixed to a value within the range of 350 – 400 K. The initial population for the genetic algorithm is 100. The stopping criteria for the genetic algorithm is 10 generations or a function tolerance of 0.0001.

For parametric analysis, the turbine inlet ammonia mass fraction and turbine inlet pressure are varied. The range of turbine inlet pressure to be studied is between 100 – 140 bar. Meanwhile, the range for initial concentration of ammonia is between 0.5 – 0.8. An ammonia-water mixture with ammonia concentration of below 0.5 are too close to the common Rankine cycle and would not be able to utilize the sliding characteristics of the mixture. Meanwhile, an ammonia concentration of above 0.8 would lead to problems in calculating the properties of ammonia-water mixture as it causes convergence issues. For every value of turbine inlet pressure and ammonia mass fraction, optimization is done to ensure maximum efficiency is obtained.

4. Results

In this chapter, the mathematical model is first validated by comparing values from similar research. Next, the result of optimization for thermal efficiency is reviewed. The effects of varying turbine inlet pressure and ammonia concentration on a Kalina cycle is then presented and discussed. The solar model results are then presented.

4.1 Model Validation

The Kalina cycle model is to be validated by comparing with previously published modelling results. Modi et al. (2016) had investigated the performance of a Kalina Cycle layout KC-12 for high temperature applications. Using the parameters set by Modi et al. (2016), the simulation is run to find the maximum efficiency and results are compared. Table 2 shows the results of model validation.

Table 2. Model validation results

Pressure at Turbine inlet (P1), bar	Ammonia mass fraction (x1)	Efficiency of reference study (Modi et al. 2016), %	Efficiency of this study, %	Percent change (%)
100	0.7	29.90	30.10	0.67
120	0.7	30.40	31.09	2.70
140	0.7	30.70	31.35	2.17
100	0.8	30.50	31.75	4.01
120	0.8	31.20	33.30	5.38
140	0.8	31.60	34.20	8.23

The average percent change in cycle efficiency when compared to previous research (Modi et al. 2016) is 3.86 %. With a low percentage change, the results can be considered valid.

4.2 Optimization Results

An example of the genetic algorithm going through generations to find the minimum fitness value is shown in Figure 2. Note that the efficiency of the Kalina cycle can be determined by subtracting fitness value from 1. From the Figure, it can be concluded that it does not take many generations for the model to find the optimum value of efficiency. In this case, the mean fitness and best fitness are found to be the same at around the 9th generation. The value of best fitness also only changes marginally from the beginning till the end. The difference between the upper and lower bounds for the decision variables may be too small and hence an optimum efficiency cycle was found quickly. A wider range of available decision variables to choose from could further improve the efficiency of the cycle.

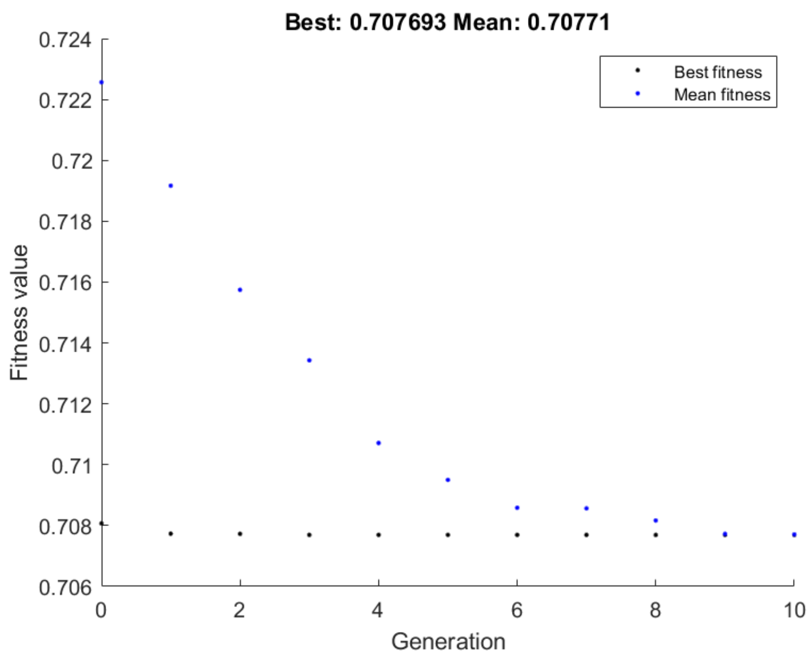

Figure 2. Best fitness plot for turbine inlet pressure of 100 bar and ammonia concentration of 0.7

From Table 3, it can be observed that for maximum efficiency, the outlet pressure of the turbine is a major contributor. For all five cases of turbine inlet pressure, the maximum efficiency is obtained when the outlet pressure is near its lower bound of 4 bar. Theoretically, the bigger the difference between turbine inlet and outlet pressures, the higher is the nett work produced as difference in enthalpy is also higher. A higher nett work produces a higher cycle efficiency. Turbine outlet pressures that are lower than 4 bar could possibly lead to a higher value of cycle efficiency. However, at low pressures of below 4 bar, many errors due to convergence issues in estimating the thermodynamic properties of ammonia-water mixture will occur and hence cannot be analysed by the simulation algorithm.

Table 3. Combination of decision variables for optimum efficiency at different turbine inlet pressure at ammonia concentration of 0.7

Turbine inlet pressure (P1) bar	Decision Variables		
	P2 (bar)	T_{10} (K)	x_{10}
100	4.005000	395.0452	0.5189
110	4.001250	398.1913	0.5279
120	4.000010	396.6690	0.5500
130	4.000039	392.0783	0.5295
140	4.010000	381.1961	0.5465

The two other decision variables, separator inlet temperature and ammonia mass fraction does not seem to have any significant impact on the efficiency for varying pressure. The table indicates that a more concentrated ammonia solution at the separator (x_{10}>0.5) is better for producing a more thermodynamically efficient cycle. There are also times when the combination of decision variables led to the thermodynamic property calculation not being able to converge. Hence, sometimes the optimizer found a solution away from the global optimum.

4.3 Effects of turbine inlet pressure on cycle efficiency

The optimum value of cycle efficiency at different turbine inlet pressures are shown in
Figure 3. From the results, the highest cycle efficiency is obtained at the highest pressure possible. At the highest inlet pressure of 140 bar, the cycle efficiency is 30.57%. Meanwhile, the lowest cycle efficiency was wound to be 28.71% at the lowest pressure which is 100 bar. Results are similar to Modi and Haglind (2015) where the turbine inlet pressure was also shown to positively impact thermal efficiency. Overall, the trend suggest that the cycle efficiency will increase when the turbine inlet pressure is increased. This theoretically makes sense, as with a larger pressure difference between turbine and condenser, the work generated should become bigger as enthalpy difference increases. This in turn should increase the cycle thermodynamic efficiency. The figure also indicates that a higher efficiency could be obtained when the pressure is increased from 140 bar.

However, it should be noted that at higher pressures of turbine inlet, supercritical operation may occur. This would require a more complicated and expensive design to handle the high amounts of pressure. Furthermore, at higher turbine pressure, the vapour quality that is exiting the turbine will decrease. Hence, the vapour quality must be checked to pass the minimum value required to prevent turbine blade erosion. In addition, the localized cost of electricity (LCOE) is very dependent on the turbine inlet pressure. High values of turbine inlet pressure can substantially increase the levelized cost of electricity, making it more expensive to implement and possibly not economically viable (Modi and Haglind 2015).

For a set condenser pressure (as in a parametric analysis), with higher turbine pressure, pressure ratio increases. This causes the vapor production rate to drop until the pressure becomes too large to produce any vapor at all. A similar effect is seen with the cooling capacity. A larger pressure ratio results in a larger temperature drop in the turbine, but the drop in vapor generation rate limits cooling at higher pressures. Hence, for power cycles, there is a limit in turbine pressure where the cycle thermodynamic efficiency will fall off. For the Kalina cycle KCS-12 using an ammonia-mass mixture, a pressure of 140 bar does not drop the vapor generation to the point where efficiency is negatively affected.

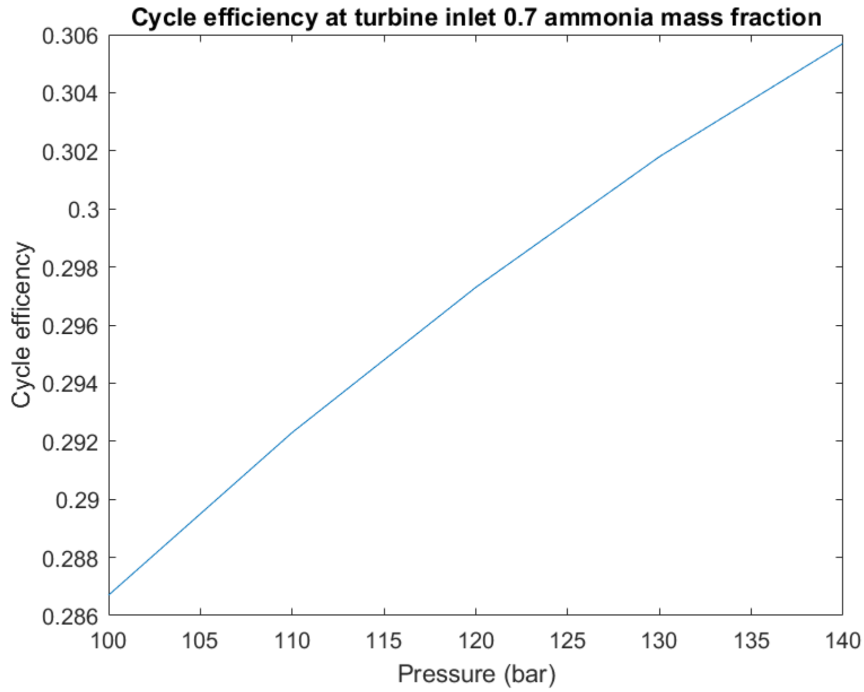

Figure 3. Effects of turbine inlet pressure on Kalina cycle efficiency

4.4 Effects of Turbine inlet ammonia concentration on cycle efficiency

The Figure 4 indicates that there is a positive relationship between the turbine inlet ammonia mass fraction and the cycle efficiency. Theoretically, it makes sense as ammonia boils at a lower temperature compared to water, which leads to more efficient usage of waste heat. Hence, a high concentration of ammonia in the beginning should lead to better efficiency. At high concentrations of ammonia mass fraction, there is little difference in efficiency between 100 bar and 120 bar turbine inlet pressure.

The maximum obtained efficiency from the whole study is 33% at an inlet ammonia mass fraction of 0.8 and inlet turbine pressure of 140 bar. The lowest cycle efficiency is 26% at turbine pressure of 100 bar and ammonia mass fraction of 0.5. The graph predicts that an ammonia mass fraction higher than 0.8 can produce better efficiency. However, this high level of ammonia concentration cannot be consistently calculated as there are many errors with the convergence of the thermodynamic property calculations. Ammonia concentration of higher than 0.8 would also lead to supercritical operating conditions to occur.

It should also be noted that when the ammonia mass concentration is increased, the bubble and dew point temperatures decrease (Knudsen et al. 2014). Compared to the use of pure water where constant evaporation occurs, this increase the exergy losses in the receiver. This is usually offset by the Kalina cycle being able to achieve higher pressure than a Rankine cycle. For a Kalina cycle with direct heat from CSP, there is no pinch point constraint on the pressure in either cycle. Simultaneously, the exergy destruction in the turbine decreases with increasing ammonia mole fraction.

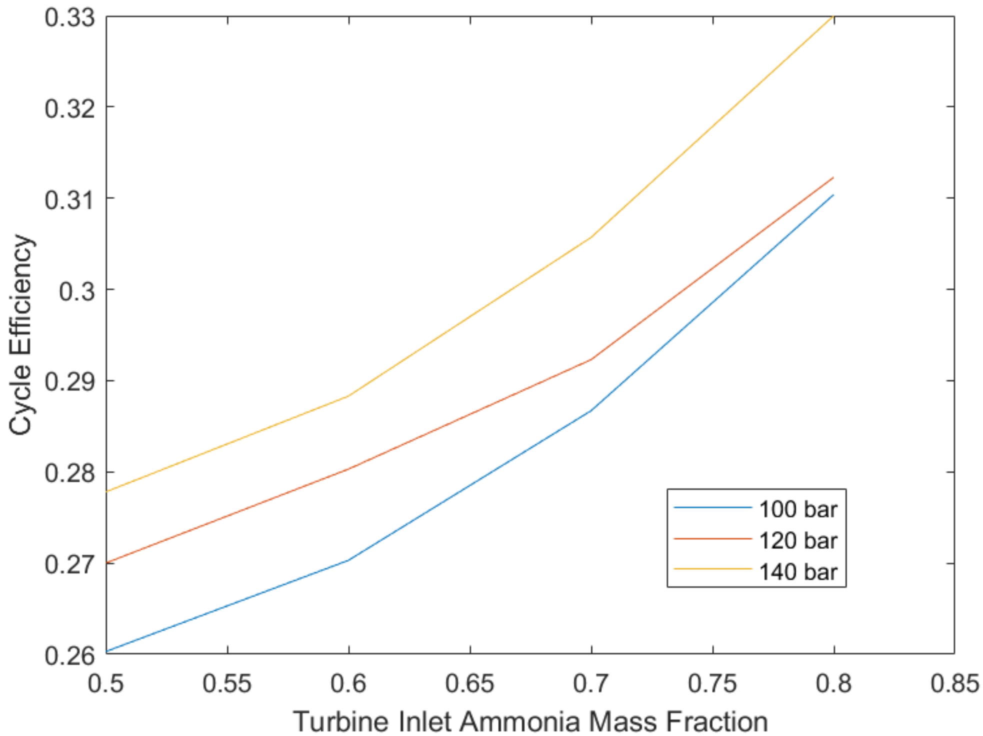

Figure 4. Effects of turbine inlet ammonia fraction on cycle efficiency at different inlet turbine pressures

4.5 Solar Model Results

From the parameters which obtained the highest cycle efficiency of 33%, the power cycle operating conditions were implemented in SAM using Linear Fresnel Direct Steam with LCOE calculator model. Table 4 shows the results.

Table 4. System Advisor Model (SAM) results

Metric	Value
Annual Energy (year 1)	6056236 kW/h
Capacity factor (year 1)	12.9%
Annual Water Usage	848 m^3
Levelized Cost of Electricity	1.46 RM/kWh

The obtained levelized cost of electricity (LCOE) is 1.46 RM/kWh. Estimated LCOE values using normally used solar technologies in Malaysia are 1.17 RM/kWh for CSP plants and 0.7 RM/kW for photovoltaic technologies (Faizal et al. 2018). Results indicate that the Kalina cycle model evaluated is more expensive than currently available solar power technologies.

5. Conclusions

Solar energy has great potential to power the Nation. Currently, the cost of implementing solar technologies are heavily influenced by the power cycle efficiency. The Kalina cycle provides an alternative to the conventional Rankine cycle that is often used. The Kalina cycle has the option of using an ammonia-water mixture as its working fluid. Ammonia-water mixture is a zeotropic mixture and its ability to lose heat are increased due to the variable temperature boiling process of ammonia water. This could provide a better cycle efficiency compared to the Rankine cycle. This ammonia-water mixture can operate up to temperatures of 400 °C. This value can be readily generated through available concentrating solar power technologies such as parabolic trough collectors and linear Fresnel reflectors.

This research studied the thermodynamic performance of the Kalina cycle at temperatures of 400 °C. A solution algorithm to determine the cycle efficiency is programmed. Optimisation using genetic algorithm is done to find the maximum efficiency with the turbine outlet pressure, separator ammonia mass fraction and separator inlet temperature chosen to be the decision variables. Results shows that the turbine outlet pressure has the most impact on the efficiency among the decision variables. Parametric analysis is done to the cycle to study the effects of turbine inlet pressure and ammonia mass concentration on cycle efficiency. An increase in turbine inlet pressure and turbine inlet mass concentration has shown to positively impact the cycle efficiency. Through optimisation, a maximum efficiency of 33.2% is obtained at a turbine inlet pressure of 140 bar and ammonia mass concentration of 0.8. Solar analysis indicates that the localized cost of electricity for the Kalina cycle is 1.46 RM/kWh, which is higher than currently used solar power technologies.

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