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FACULTY OF ENGINEERING

THERMODYNAMIC ANALYSIS OF KALINA CYCLE

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Thermodynamic Analysis of Kalina Cycle

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ABSTRACT

Thermodynamic Analysis of Kalina Cycle

Due to the continuous increase in the world population and technological developments, people's need for energy is increasing day by day. Scientists and researchers are working on different energy production methods to satisfy people's energy needs. Meanwhile, they are conducting various researches both to prevent energy waste and to find eco-friendly solutions. The researchers designed a cycle to use more of the waste heat generated by the power plant system to increase system efficiency. This cycle was called the Kalina cycle by its creator, Alexander Kalina. The Kalina cycle is a cycle that can achieve high efficiency from low temperature, which is now accepted worldwide in converting heat to electricity.

In this report, effects of temperature, pressure and mass flow on power production and efficiency of Kalina cycle are investigated.

SYMBOLS

h	: specific enthalpy (kJ/kg)
$\dot{m}$	: mass flow rate (kg/s)
P	: pressure (bar)
q	: quality
$\dot{Q}$	: rate of heat transfer (kW)
s	: specific entropy (kJ/kg K)
T	: temperature (Kelvin)
$\dot{W}$	: power (kW)
X	: concentration
1,2,3 ... ,12	: number of state-points
ρ	: density

SUBSCRIPTS

cond	: condenser
p	: pump
is	: isentropic
min	: minimum
max	: maximum
in	: input in the HE

ABBREVIATIONS

HE	: heat exchanger
HTR	: high temperator recuperator
LTR	: low temperator recuperator
TTD	: terminal temperature difference
KCS	: Kalina cycle system
ORC	: Organic Rankine cycle
EES	: Engineering Equation Solver

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1. Introduction

Capturing waste heat of energy generation plants and other industrial processes to produce power can not only mitigate energy shortage we are facing but also concurrently address the issue of global warming. Carnot cycle is the ideal cycle; it provides an upper limit on the efficiency that any classical thermodynamic engine can achieve during the conversion of thermal energy into work but this cycle is a theoretical cycle. Therefore, other applicable cycles are used to generate power from heat sources [1].

The most well known and encountered power cycle to produce power from heat is Rankine Cycle [2]. But for low temperature applications, Rankine cycle has very low efficiency. In order to produce power from low temperature waste heat, different cycles are proposed such as: Organic Rankine Cycle (ORC) and the Kalina Cycle. For ORC, selection of fluid and the design of the occupied turbine (expander) is an important task [3].

Kalina cycle is a thermodynamic cycle which is proposed to convert low temperature waste energy to usable energy [4]. Kalina cycle is a new concept in heat recovery and power generation that uses a mixture of ammonia and water as the working fluid and has the potential for significant efficiency gains over the conventional Rankine cycle. Ammonia-water mixture is the most often used working fluid of Kalina cycle. The composition of the system's working fluid changes while system operation, which allows the system to achieve high thermodynamic efficiencies. First-generation Kalina cycle systems are only applicable to relatively low temperature heat sources [5]. On the contrary, second generation Kalina cycle systems have been developed by Alexander Kalina and Kalex LLC for application to both low and relatively high temperature heat sources [6]. For low-temperature heat sources, second-generation Kalina cycles are projected to achieve higher thermal efficiencies than first-generation cycles [7].

In their research, Ibrahim and Kovach concluded that the Kalina cycle reduces thermal pollution from condenser and reduces combustion by products such as CO_2, SO_2 etc. The Kalina cycle has also been used to efficiently recover heat from solar power [8].

In addition to the conventional version, variants of the Kalina cycle are also recommended such as: Kalina Split Cycle. In the Split Cycle, the ammonia concentration is varied throughout the evaporation process to achieve a temperature profile that matches better with the heat source. Ulrik Larsen [9] compared the conventional Kalina Cycle with the Kalina Split cycle and found that the Split Cycle process can achieve 20% higher efficiency, than that of conventional Kalina cycle. But higher complexity and installation cost are disadvantages of split cycle. Exergy analysis of the Kalina Split Cycle is performed by Tuong-Van Nguyen and the exergetic efficiency of the Kalina Split Cycle is 2.8% higher than the conventional Kalina Cycle [10].

2. Kalina Cycle

2.1. Main Parts of the Kalina Cycle

Main components which consist of a Kalina cycle are seen below figures:

Heat Exchanger (HE):

Waste heat from the low temperature source is transferred to the Kalina cycle plant via a heat exchanger. This waste heat is absorbed by the binary mixture, which is the working fluid of the Kalina cycle. Ammonia-water solution is used as the working fluid in the Kalina cycle.

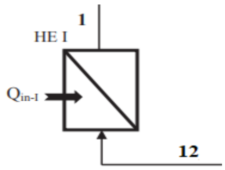

Figure 1: Heat exchanger

Separator:

A steam separator, also called a moisture separator o r a steam dryer, is a device that separates water droplets from steam.

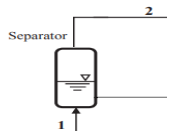

Figure 2: Separator

Turbine:

The part that converts the kinetic energy of a fluid into mechanical energy.

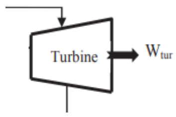

Figure 3: Turbine

Recuperators (HTR and LTR):

The recuperator is a counter flow heat exchanger used to recover the waste heat. It is based on the principle of counter flowing fluids transferring heat to each other.

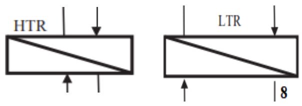

Figure 4: High temperature and low temperature recuperators

Condenser:

It is a heat exchange element used to spread the cold air to the environment by condensing the refrigerant liquid.

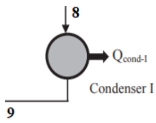

Figure 5: Condenser

Pump:

The feed pump is used to pump the condensed working fluid to the required high pressure.

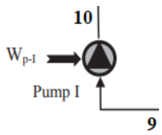

Figure 6: Pump

Valve:

The valve is used to reduce the pressure of the fluid to its desired low pressure.

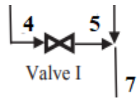

Figure 7: Valve

2.1. Types of Kalina Cycle

Kalina cycle designs are classified based on the source of heat, application field, and temperature of the heat source. Kalina cycle types are listed in Table 1.

Table 1: Types and Applications of Kalina Cycle [11]

Kalina Cycle System 1 (KCS 1)	Bottoming cycle small plants
Kalina Cycle System 2 (KCS 2)	Low temperature geothermal
Kalina Cycle System 3 (KCS 3) :	High temperature geothermal and industrial waste
Kalina Cycle System 4 (KCS 4)	Cogeneration
Kalina Cycle System 5 (KCS 5)	Direct-fired for coal and other solid fuels
Kalina Cycle System 5 (KCS 5n)	High temperature gas-cooled nuclear reactor
Kalina Cycle System 6 (KCS 6)	Bottoming for utility combined cycle
Kalina Cycle System 7 (KCS 7)	Direct fired, split cycle
Kalina Cycle System 8 (KCS 8)	Bottoming cycle, split cycle
Kalina Cycle System 9 (KCS 9)	Retrofit subsystem for existing plant
Kalina Cycle System 11 (KCS 11)	Exploiting low temperature heat sources.
Kalina Cycle System 12 (KCS 12)	Low temperature geothermal.
Kalina Cycle System 34 (KCS 34)	Exploiting low temperature heat sources.

2.2. Comparison of Kalina Cycle with the Rankine/ORC Cycle

In thermodynamics, the Carnot cycle is defined as the most efficient thermal cycle which consist of four reversible, two isothermal, and two adiabatic processes.

Kalina cycle is primarily a "modified" Rankine cycle. Kalina include proprietary system designs that specifically exploit the advantages of ammonia-water working fluid. These distinctive designs, applied individually or integrated with each other in a number of different combinations, form a unique family of Kalina cycle systems.

2.3. Working Fluid

Electricity generation has recently sparked and become famous. However, conventional energy is not always economically viable due to capital costs and high fuel costs. In this case, the use of non-conventional cycles becomes an important factor in studies to meet energy needs. The efficiency of unconventional cycles is highly dependent on fluid selection. The heart of the Kalina cycle is the ammonia – water mixture as a functional stream. Ammonia – water mixtures have some basic properties unlike pure water or pure ammonia. The combination of the two liquids works completely like a fresh substance [12].

Table 2: Advantages and Disadvantages of Ammonia-Water Solution [13]

Advantages	Disadvantages
• It can work at low evaporation temperatures. • The lighter component (ammonia) provides efficient waste heat. • Ammonia is readily available and relatively cheap. • Higher productivity • No crystallization of the vacuum problem • Water has a strong affinity for ammonia, and they dissolve with each other under the wide operating conditions that occur in different refrigeration applications. • The solution is highly stable.	• Rectifier need leads to more complex systems.

3. Kalina Cycle Applications

Because of this ability to take full advantage of the temperature difference between the particular heat source and sink available, it finds applications in reuse of industrial process heat, geothermal energy, solar energy, and use of waste heat from power plants. Kalina cycle is also ideally suited for applications such as steel, coal, oil refineries and cement production plants.

Several plants are now operating successfully worldwide using different heat sources as in the Table 3. All of these show efficiency gains over a conventional Rankine Cycle, as predicted by thermodynamic modeling software. [14,15]

Table 3: Worldwide Kalina Cycle Case-Studies

Name	Country	Commissioned	Output (MW)	Heat source
Canoga Park	USA	1992	6.5	Nuclear waste heat
Fukuoka	Japan	1998	4	Waste incineration
Sumitomo Metals	Japan	1999	3.5	Waste heat
Husavik	Iceland	2000	2	Geothermal
Fuji Oil	Japan	2005	3.9	Waste heat
Bruschal	Germany	2009	0.6	Geothermal
Unterhaching	Germany	2009	3.5	Geothermal
Shanghai Expo	China	2010	0.05	Solar hot water
Quingshui	Taiwan	2011	0.05	Geothermal

3.1. Canoga Park

Canoga Park is the first large-scale power plant operated using the Kalina cycle and was built with support from the United States Department of Energy (DoE) to demonstrate the technology.

In the initial configuration, the power source was waste heat from a nuclear steam generator test facility. When this is not possible, waste heat from gas turbines is used as an alternative. The equipment has been operating with good reliability for a total of more than five years (1992-1997) and has accumulated approximately 10,000 operating hours. The only major material issue is the steam turbine labyrinth seals, which are pure nickel as recommended by the manufacturer.

Due to the limited data available at the time regarding the use of the material in the ammonia atmosphere at the high temperatures and pressures of this device, the performance of the steam turbine was satisfactory, although the construction materials are generally nickel base alloys.

3.2. Fukuoka

Also seen as a demonstrator, the construction of this unit was subsidized by the Japanese Ministry of International Trade and Industry (MITI), making it the first waste incineration plant to use the Kalina Cycle. As a result, it achieved 20% more efficiency than other similar plants of this type.

3.3. Sumitomo Metals (Kashima Works)

Founded at Sumitomo Steel's Kashima Works, the Kalina Cycle Power Plant is the first commercial application of the Kalina Cycle and has produced 3.5 MW of electrical capacity for more than ten years of successful operation. The unit successfully passed the plant performance test in the fall of 1999 and has been operating with high availability since.

3.4. Husavik

The Husavik Geothermal Plant in Iceland began operations in 2000, using a 121°C brine flow to provide 80% of the small town's electricity needs. The working fluid is 82% ammonia water at a pressure of 3 bar.

Completed in November 2001 after 15 months of performance testing. Even with a brine temperature 3°C lower than the design temperature (which is quite significant considering the thermodynamics of the system), the plant still develops a capacity of about 1.7 MW, meeting the public performance test requirements of the plant.

A few years later, this unit had difficulties in operation and a series of production shutdowns occurred. Although there are a number of reasons for the relatively poor reliability, there are two main factors identified by Reproducible Engineering and others that contribute significantly to poor performance. The first of them; poor water quality control and non-compliance with operating instructions provided by the OEM. The other is; equipment was not acid cleaned prior to operation as recommended by the supplier, which meant that debris from fabrication and manufacturing was not removed.

3.5. Fuji Oil

The Fuji Oil 4MW waste heat plant, commissioned in 2005, uses heat from two sources, a light hydrocarbon vapor and low pressure steam, as part of a waste heat-to-electricity conversion project at the Fuji Oil refinery in Chiba, Japan. The project was the first successful integration of waste heat generation technology with the Eureka process for hydrocarbon processing. The temperature of the waste heat is 118°C and the plant has been running continuously since it was commissioned with almost 100% availability between planned outages.

The unit was constructed to demonstrate the Kalina Cycle in this application to the National Institute of Science and local government. The heat source is a low temperature thermal well with a geothermal fluid temperature of 110°C. The plant was commissioned and tested in the first months of 2011.

3.6. Shanghai Expo

Exclusive Kalina Cycle license holder for China, Shanghai Shenghe New Energy Resources Science and Technology Co Ltd (SSNE), installed the world's first solar thermal Kalina Cycle power plant at the 2010 Shanghai World's Fair.

SSNE has installed conventional solar water heaters on the 3000 m^2 roof of the Expo Corporate Pavilion. The facility used 90-95 °C water and produced approximately 50kW until it was dismantled at the end of the event.

4. Significant Operational Elements for Kalina Cycle

4.1. Material Selection

Successful application of the Kalina Cycle technology with various heat sources provided the validation of fundamental thermodynamic principles as well as the long-term performance of the materials used for critical components in these applications.

Various alloys are selected for heat exchangers, separators and related components, and for pipes operating under the modest temperature and pressure conditions of Kalina Cycle applications.

The turbine materials used in Kalina Cycle systems are those that will often be used in typical axial flow steam turbines or radial flow turboexpanders operating at the temperatures and pressures characteristic of power plant application [14].

4.2. Water Quality Control

As with any power plant, ensuring good water quality is essential for reliable operation of the Kalina Cycle system. Water treatment is an important factor in preventing corrosion, scaling and contamination of the working fluid, and the required water quality is also highly dependent on the operating temperature. This, in turn, affects the reactivity of the chemical and decomposition processes. In Kalina Cycle systems, the fluid temperature is significantly lower, so water quality control is simpler.

Key processes for maintaining good water quality are: softening to reduce sulphate, chloride, and nitride ions; deaeration to reduce the amount of gas; and good pH control. These processes are important to ensure the quality of the small amount of make-up water used in the Kalina Cycle power plant. In this case, however, the pH is controlled by the ammonia content of the liquid, which generally gives a pH of about 10. Demineralization is carried out using synthetic anion and cation exchange resins. Dissolved gases such as oxygen and, in some cases, CO_2, can be removed with a commercially available deaeration unit.

4.3. General Corrosion

To reduce the overall risk of corrosion in boilers, water treatment methods are used to create conditions of high pH values and low oxygen levels to encourage the growth of protective magnetite (Fe_3O_4) layers on pipe surfaces.

The presence of ammonia (NH_3) in the Kalina Cycle environments provides strongly alkaline conditions and pH values of about 10 are expected as a result. This means that the steel surfaces will be passivated and the growth of magnetite layers will be encouraged. A limitation in this regard is that in many cases the kinetics of oxide growth is slow due to the relatively low fluid temperatures in the range of 100-350°C.

4.4. Localised Corrosion

There is always a risk of localized corrosion in crevices or pits when foreign substances such as chloride ions are present in the water supply. Corrosion will occur even when the impurity content is relatively low because concentration can build up in the pit or gap and this will drive the corrosion process.

Similarly, where deposits form on the metallic surface, a microclimate may develop below the deposit, possibly as a result of interaction with impurities in the deposit. This allows the corrosive attack to occur locally. This is why demineralization is important to remove impurities such as chlorides. Similarly, good control of water chemistry will minimize the build-up of impurities.

4.5. Nitriding

When steel is exposed to ammonia environments at high temperature, surface nitriding can occur as a result of decomposition of the ammonia to yield nascent nitrogen. This diffuses into the steel to form a nitride layer. An important point is that the steel acts as a catalyst, without which no decomposition would occur.

If the catalytic surface is 'poisoned' by some impurity, the nitriding rate is greatly reduced. When strong nitride formers such as Cr, Al or V are present, these elements will preferably be nitrided and form a hard wear resistant layer. A critical difference between nitride formation in ammonia vapor and commercial processing is that the latter is carried out in a reducing environment and oxide deposit formation is prevented, thereby providing a wear-resistant surface.

It is known that nitride formation rates increase at atmospheric pressure and this is consistent with the thermodynamics of ammonia decomposition. Therefore, an increase from ambient pressure to 20 bar reduces the attack rate, but at much higher pressures there is only a slight further reduction. Since nitriding is a diffusion-controlled process, the kinetics of nitride formation will be highly dependent on temperature.

4.6. Stress Corrosion Cracking (SCC)

SCC occurs in ferritic steels, under certain combinations of stresses and in certain corrosive environments, when corrosive conditions cause a local failure of the protective oxide layer that is sufficient to initiate a crack. The presence of pitting or oxide inclusions may be enough to trigger crack initiation. In general, the risks of SCC in liquid ammonia storage tanks increase with higher yield strength materials, as well as in welds with insufficient post-weld heat treatment.

It should be noted that the stresses required to initiate a crack are generally higher than those encountered in normal operation and can be attributed, together with the applied stress, to the presence of residual stresses from the manufacturing process or from higher strength welds, which may be sufficient to initiate cracking, particularly in the presence of oxygen.

From the perspective of the Kalina Cycle system, SCC is unlikely to be a problem to occur in practice and no evidence of SCC has been observed at any of the operating Kalina

Cycle facilities. The steels generally used are not high strength steels and SCC is more common in high yield strength steels. Also, the medium is one of ammonia-vapor and the presence of water will have an inhibitory effect. As SCC is normally associated with 'wet' surfaces, the risk will only apply in areas where condensation from the vapor phase is occurring.

5. Thermodynamic Analysis of Kalina Cycle

In this our study we aim to perform the thermodynamic analysis of Kalina cycle (KCS 34). Our main purpose is to understand details of its operational mechanism. On this progress we use software for analysis every stage of Kalina Cycle.

Our project is based on design and analysis result of design. And this type of structural projects has multiple options when starting to flow chart. We have some important values for analysis and design of flow chart. On our project we focus on three result variables from result that these are Maximum Power Production, Minimum Power Input, Minimum Heat Input. Dependent parameters that change based on where the intended system will be utilized are an excellent place to start designing. Between of three variables the most important variable is power production for us. That is why we focus on this criterion for starting design.

5.1. Operational Mechanism

Schematic of considered Kalina cycle is seen in Figure 8.

In order to obtain as much steam as possible, heat is transferred to the working fluid and hence, working fluid leaves the heat exchanger at high temperature and pressure. After the heat exchanger, working fluid enters into the separator (state point 1). In the separator, ammonia-water solution is separated into saturated rich vapor (state point 2) and saturated weak liquid (state point 3). The saturated rich vapor enters into the turbine and expands to state point 6 to generate power (state points 2-6). While the saturated weak liquid passes through high temperature recuperator (HTR), it transfers heat to the lower temperature solution (state point 11) which comes from the low temperature recuperator (LTR) to increase the temperature of the working fluid before entering into the HE. Throttling valve is used to reduce the pressure of the weak liquid to the turbine exit pressure (state points 4-5). Afterwards, the ammonia-water solution (state point 7) is reformed by mixing the weak liquid (state point 5) with the rich solution (state point 6) before entering into the condenser. As the solution from state point 7 passes through the LTR to state point 8, it transfers heat to the lower temperature solution which comes from state point 10, so the working fluid temperature gets higher than state point 10 at state point 11. As the working fluid passes through the condenser (state point 8-9), it rejects heat to the environment. The pump is used to increase the pressure of the binary mixture liquid (state point 10). Then the binary mixture fluid enters the evaporator (state point 12) and the loop is closed

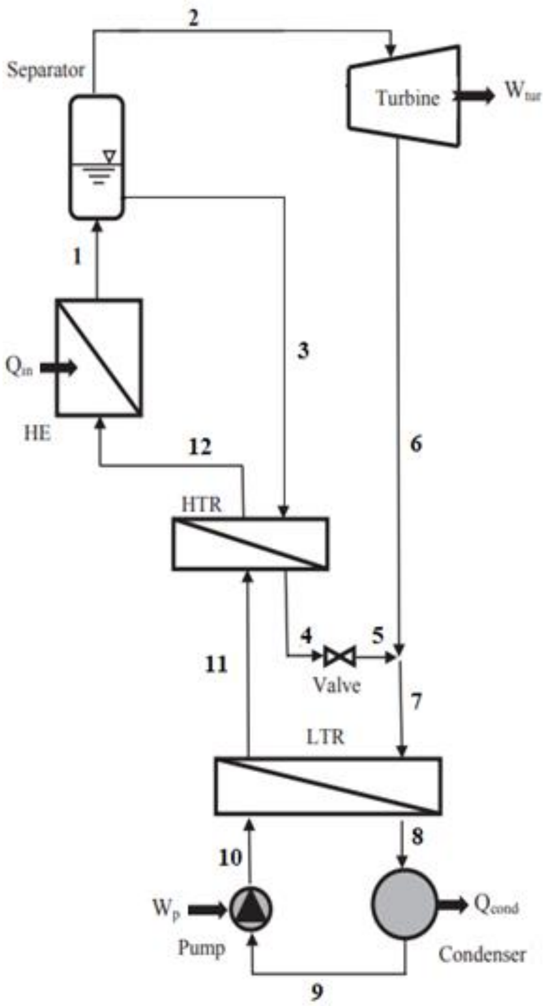

Figure 8: The schematic representation of Kalina cycle

5.2. Thermodynamic Analysis

Analysis is performed by applying mass, energy and momentum balance equations successively.

$$E_{in} - E_{out} = \Delta E_{System} \tag{1}$$

For Kalina cycle, energy inlet and outlet from system balanced and equal each other.

$$E_{inlet} = E_{outlet} \tag{2}$$

$$Q_i + W_i + \sum m_i \left(h_i + \frac{{V_i}^2}{2} + g(z_i) \right) = Q_e + W_e + \sum m_e \left(h_e + \frac{{V_e}^2}{2} + g(z_e) \right) \tag{3}$$

Neglecting the kinetic and potential energy change, mass and energy balance equations are presented below.

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{4}$$

$$\sum \dot{Q} + \sum \dot{m}_i h_i = \sum \dot{w} \sum \dot{m}_e h_e \tag{5}$$

Table 4: The thermodynamic equations for devices used in Kalina Cycle

Components	Formula
Separator	$\dot{m}_1 \cdot h_1 = \dot{m}_2 \cdot h_2 + \dot{m}_3 \cdot h_3$
Turbine	$\dot{W}_{turbine} = \dot{m}_2 \cdot (h_1 - h_6)$
Turbine Efficiency	$\eta_{turbine} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,is}} = \frac{h_2 - h_6}{h_2 - h_{6,is}}$
Condenser	$\dot{Q}_{Cond} = \dot{m}_8 \cdot (h_8 - h_9)$
LT Recuperator	$\dot{m}_{11}(h_{11} - h_{10}) = \dot{m}_7(h_7 - h_8$
HT Recuperator	$\dot{m}_3(h_3 - h_4) = \dot{m}_{11}(h_{12} - h_{11})$
Throttle Valve	$\dot{m}_4 \cdot h_4 = \dot{m}_5 \cdot h_5$
Pump	$\dot{W}_{pump} = \dot{m}_9 \cdot (h_{10} - h_9)$
Pump Efficiency	$\eta_{pump} = \frac{\dot{W}_{pump,is}}{\dot{W}_{pump}} = \frac{h_{10,is} - h_9}{h_{10} - h_9}$
Evaporator	$\dot{Q}_{in} = \dot{m}_1 \cdot (h_1 - h_{12})$

5.3. Mathematical Model and Computational Programming

In the analysis of Kalina Cycle, applied assumptions are listed below:

- Steady-state, one dimensional, frictionless flow.
- Condenser rejects heat to the environment.
- Pressure loss is neglected through the heat exchangers, condenser, evaporator and pipes.
- Working fluid leakage is neglected.
- Valve and throttling processes are isenthalpic.
- The saturated vapor and saturated liquid streams existing the separator are rich and weak ammonia-water stream, respectively.
- The kinetic and potential energy changes are ignored.

EES software was used to simulate the entire Kalina cycle. The mathematical formulas ran on the system with entry values. After that, results are received from the software.

5.4. Computational Modeling

Inputs of the program are: turbine inlet temperature (T_2), pressure at boiler (P_{max}), ammonia mass fraction of total working fluid (x_1), mass flow rate through separator inlet ($\dot{m}_{total}$), temperature at condenser outlet (T_9), and isentropic efficiencies of turbine and pump ($\eta_{turbine}, \eta_{pump}$).

$$x = \frac{\dot{m}_{NH3}}{\dot{m}_K} \tag{6}$$

$$P_{max} = P_1=P_2=P_3=P_4=P_{10}=P_{11}=P_{12} \tag{7}$$

$$T_1=T_2=T_3 \tag{8}$$

$$P_{min}=P_5=P_6=P_7=P_8=P_9 \tag{9}$$

$$q_1 = q_2 = 1 \tag{10}$$

$$q_9 = q_3 = 0 \tag{11}$$

$$x_1 = x_7 = x_8 = x_9 = x_{10} = x_{11} = x_{12} \tag{12}$$

$$x_2 = x_6 \tag{13}$$

$$x_3 = x_4 = x_5 \tag{14}$$

$$\dot{m}_1 = \dot{m}_7 = \dot{m}_8 = \dot{m}_9 = \dot{m}_{10} = \dot{m}_{11} = \dot{m}_{12} \tag{15}$$

$$\dot{m}_2 = \dot{m}_7 \tag{16}$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_5 \tag{17}$$

In the equations P, T, q, x, and m are pressure, temperature, quality, concentration, and mass flow rate of the ammonia-water solution at state's points, respectively.

For the separator, the mass balance equation for ammonia-water solution and ammonia is presented as the following:

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \tag{18}$$

$$\dot{m}_1 x_1 = \dot{m}_2 x_2 + \dot{m}_3 x_3 \tag{19}$$

Specific enthalpy of the ammonia-water solution at the turbine exit (h_6) is computed as follows:

$$\eta_{turbine} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,is}} = \frac{h_2 - h_6}{h_2 - h_{6,is}} \tag{20}$$

Where h is the specific enthalpy of the ammonia water solution at subscripted state points. At Eq. (20) $h_{6,is}$ is specific enthalpy of ammonia water solution at the end of an isentropic process. $\dot{W}_{turbine}$ is the power generation of the turbine, $\dot{W}_{turbine,is}$ is the power generation isentropic turbine.

Hence applying conservation of energy to the turbine, $\dot{W}_{turbine}$ is determined by the following Eq. (21):

$$\dot{W}_{turbine} = \dot{m}_2 \cdot (h_2 - h_6) \tag{21}$$

$$\dot{Q}_{in} = \dot{m}_1 \cdot (h_1 - h_{12}) \tag{22}$$

Applying the principle of conservation of mass to the mixing process of ammonia-rich solution and ammonia-weak solution, Eq. (23) is obtained.

$$\dot{m}_7 h_7 = \dot{m}_5 h_5 + \dot{m}_6 h_6 \tag{23}$$

The isenthalpic process in valve can be expressed as:

$$h_4 = h_5 \tag{24}$$

As for the processes in LTR and HTR, below equations are applied.

$$\mathrm{T}_{11} = \mathrm{T}_7 - TTD \tag{25}$$

$$\dot{m}_3 \cdot (h_4 - h_5) = \dot{m}_{11} \cdot (h_{12} - h_{11}) \tag{26}$$

Specific enthalpy of the ammonia-water solution at the pump exit is presented as h_{10}.

$$\eta_{pump} = \frac{\dot{W}_{pump,is}}{\dot{W}_{pump}} = \frac{h_{10,is} - h_9}{h_{10} - h_9} \tag{27}$$

Hence, power consumption of the pump $\dot{W}_{pump}$ is determined by the following equation:

$$\dot{W}_{pump} = \dot{m}_9 \cdot (h_{10} - h_9) \tag{28}$$

Energy balance equation of LTR is given below to determine the thermodynamic properties at condenser inlet.

$$\dot{m}_{11} \cdot (h_{11} - h_{10}) = \dot{m}_7 \cdot (h_7 - h_9) \tag{29}$$

The rate of heat rejection from condenser $\dot{Q}_{cond}$ is determined by applying energy balance equation to the condenser as following:

$$\dot{Q}_{cond} = \dot{m}_8 \cdot (h_8 - h_9) \tag{30}$$

The efficiency of cycle is calculated with following equation:

$$W_{net} = W_{turbine} - W_{pump} \tag{31}$$

$$\eta = \frac{W_{net}}{Q_{in}} \tag{32}$$

6. Results & Discussion

In this study, Kalina cycle thermodynamic analysis is carried out. A computational program is developed in EES software. Results of the performed analysis are presented below. In the analysis thermodynamic properties of ammonia-water binary mixture working fluid is taken from EES database. Program inputs are some of the operational parameters of the Kalina cycle which are tabulated in Table 5. While the analysis of variation in one parameter, the other parameters are kept constant as reported in Table 5. In the analysis, effect of variation in turbine inlet pressure (P_2), turbine inlet temperature (T_2) and concentration of the ammonia-water mixture (x_1), working fluid on net power production (W_{net}) and cycle efficiency (η) is investigated.

Table 5: Operational parameters and boundary condition of Kalina Cycle

Rate of heat transfer to the Kalina Cycle - $\dot{Q}_{in}$ (kW)	500
Temperature at turbine inlet - T_2 ($°F$)	393,15
Pressure turbine inlet - P_2 (bar)	35
Temperature at Condenser exit -T_9 ($°F$)	298,15
Concentration of NH_3-H_2O basic solution - x_1(%)	70
Isentropic efficiency of pump - η_{pump} (%)	80
Isentropic efficiency of turbine - $\eta_{turbine}$ (%)	80
Terminal temperature differences of LTR-TTD ($°F$)	10
Mass flow rate of the ammonia -water basic solution - $\dot{m}_1$	0.98

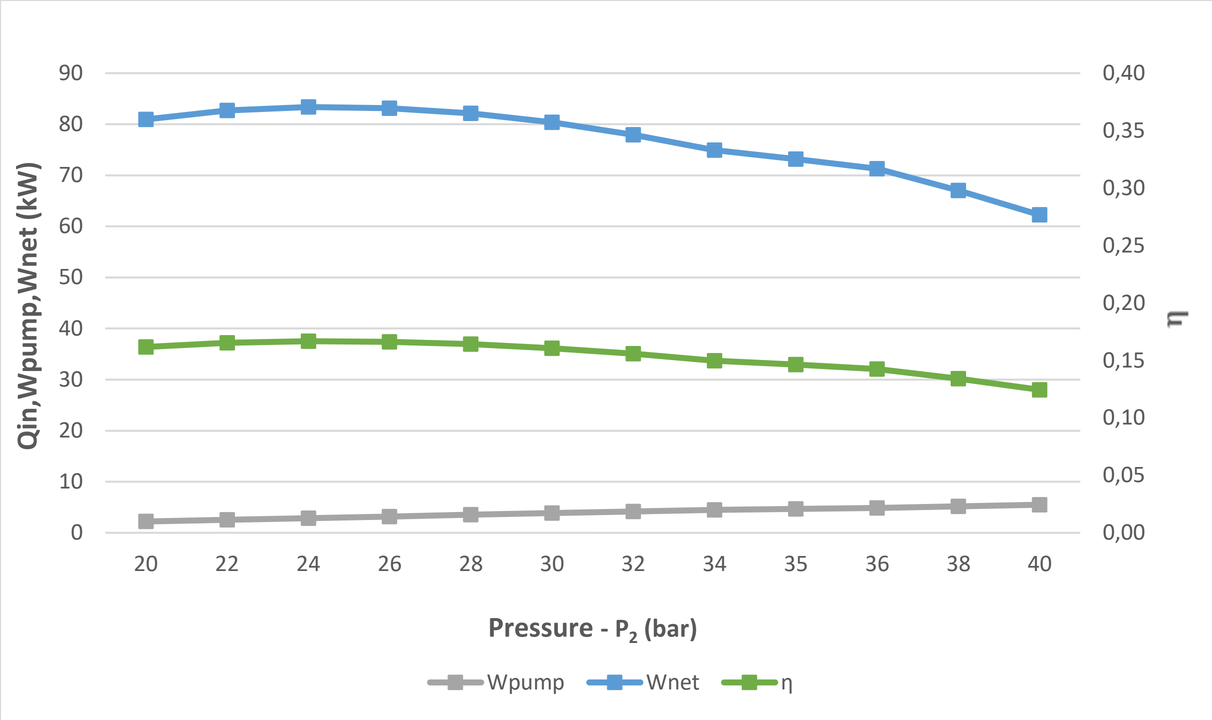

Figure 9: Variation of W_{net}, η, and W_{pump} with turbine inlet pressure (P_2)

In Figure 9, W_{net}, η, and W_{pump} results of the Kalina cycle with respect to variation of P_2 is presented. It is seen in Figure 9 that variation of W_{pump} is quite limited. Efficiency of cycle (η) and net work production (W_{net}) of the cycle is increasing with rising turbine inlet pressure but, after a certain value of P_2 increase of turbine inlet pressure causes a decrease in η and W_{net}. This decreasing trend emerges from constant turbine exit pressure. Enthalpy difference between turbine inlet and outlet fluxes $(h_2 - h_6)$ increases with rising P_2. Based on Eq. (21), W_{net} is ascenting. This the efficiency of cycle at same time increases, based on Eq. (32). On the other hand, as P_2 increases, the mass flow rate of the rich ammonia-water binary mixture ($\dot{m}_2$) solution decreases. Based on Eq. (21), mass flow rate ammonia rich vapor flow $\dot{m}_2$ mainly effects the resulting $\dot{W}_{turbine}$. As a result, after a certain P_2, both of the W_{net} and η decrease in Figure 9.

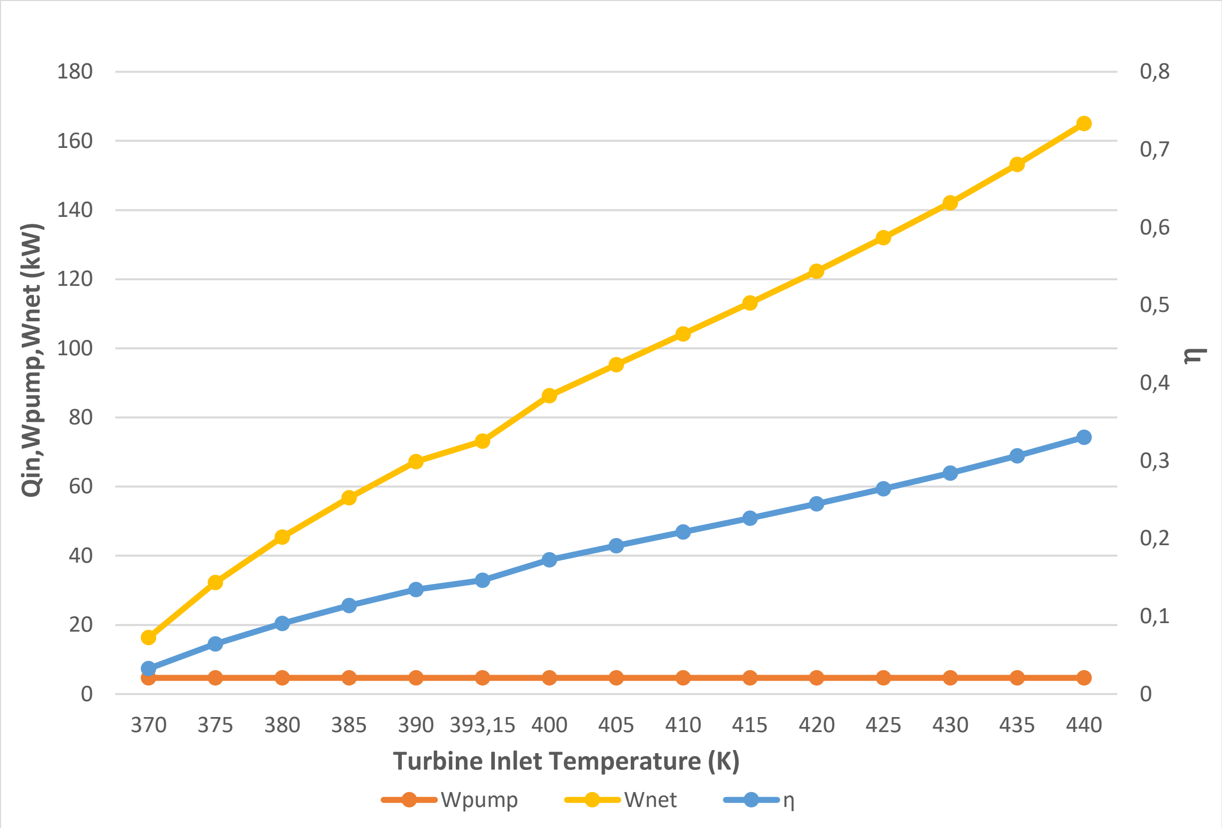

Figure 10: Variation of W_{net}, η, and W_{pump} with turbine inlet temperature (T_2)

In Figure 10, W_{net}, η, and W_{pump} results of the consider Kalina cycle with respect to increasing turbine inlet temperature (T_2) is presented. It is specified that as the turbine inlet temperature increases, inlet and outlet turbine enthalpy difference $(h_2 - h_6)$ increases and W_{pump} increases, based on Eq, (28). On the other hand, the mass flow rate $(\dot{m}_2)$ and concentration (x_2) increase with rising (T_2). Due to the mass flow rate and enthalpy difference increase, W_{net} increases. W_{net} increase leads efficiency of the cycle (η) to grow, as seen in Figure 10.

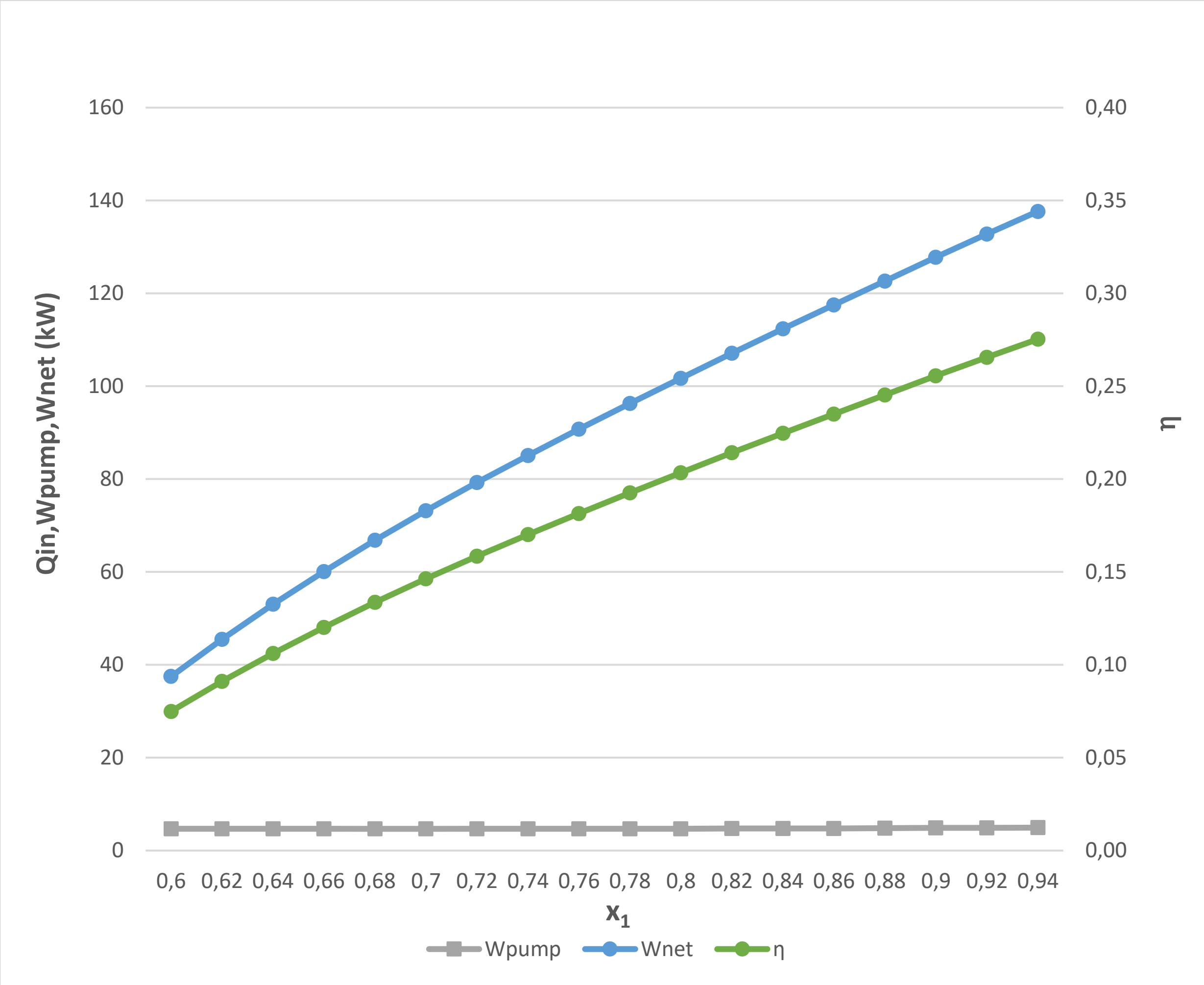

Figure 11: Variation of W_{net}, η, and W_{pump} with concentration of ammonia-water solution (x_1)

In Figure 11, W_{net}, η, and W_{pump} results of the consider Kalina cycle with respect to ammonia-water basic solution concentration (x_1) is presented. It is determined that at constant temperature (T_2), mass flow rate rich ammonia-water vapor ($\dot{m}_2$) that is delivered to the turbine increases. With increasing concentration (x_1) of ammonia-water basic solution the amount of ammonia vapor at HE gets higher. The power production of the turbine ($\dot{W}_{turbine}$) and work done by the cycle (W_{net}) are proportion to mass flow rate of ammonia-rich vapor transfer to the turbine ($\dot{m}_2$), W_{net} and η gets higher as (x_1) increases based on Eq. (21), Eq. (31), and Eq. (32).

7. Conclusion

In this research, effect of selected operation parameters (turbine inlet pressure (P_2), turbine inlet temperature (T_2) and concentration of the ammonia-water mixture (x_1)) on Kalina cycle net power generation (W_{net}) and efficiency (η) is analysed. Based on presented mathematical model, cycle simulation software developed to provide an in-depth analysis for cycle thermodynamics mechanism. Results are obtained by changing a parameter of the Kalina cycle based on these analysis. Within above results (Figure 9, Figure 10, Figure 11), it is determined that the cycle is a whole, and although the other parameters remained constant, the change in a parameter also affected the efficiency of the cycle and the work done. As a result, it was seen that all the equations in the mathematical model were interrelated and a change in the parameters affected the results of all the equations separately. As a final result, Kalina cycle provides that the waste energy can be converted into usable energy. And also, Power production with Kalina cycle provides environmentally friendly power production and helps making the world cleaner.

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