Performance Evaluation of a Kalina Cycle using a Novel Extended Thermodynamic Analysis

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Abstract

This research presents a novel extended thermodynamic analysis method (ETAM) which helps to answer the question that, the improvement of which equipment in a thermodynamic cycle is in priority. This novel analysis has three parts, including extended energy, extended entropy, and extended exergy analyses. As a case study, a low-temperature geothermal Kalina cycle system-34 was analyzed. The results of conventional exergy analysis method (CEAM), advanced exergy analysis method (AEAM), and proposed novel method were compared with each other. CEAM indicated that the condenser has the largest exergy destruction, followed by the evaporator, and turbine. In contrast, according to AEAM, the first improvement priority should be given to the condenser, followed by the turbine and LTR. The improvement priority using the presented novel extended analysis was also given to the condenser, turbine, and LTR, which is the same as the results of AEAM, while the proposed novel method is less complicated compared to the AEAM.

Keywords: Extended thermodynamic analysis; Advanced exergy analysis; Conventional exergy analysis; Kalina cycle; improvement priority.

1. Introduction

Exergy is the largest possible beneficial work that can be achieved from a system at a given state in a defined environment [1]. The conventional exergy analysis method (CEAM) plays a crucial role in calculating the irreversibilities of the system components. Hatami et al. [2] investigated an indirect solar dryer. The outcomes of the energy and exergy evaluation show more stream exergy for higher speed of air and hence, lower irreversibility. Ghorbani et al. [3] studied a wind farm integrated with compressed air energy storage that uses phase change material. According to the results of energy and exergy analysis, exergy efficiency and round-trip efficiency, reach 80.71% and 70.83%. Elhelw et al. [4] analyzed a 650 MW thermal power plant based on
exergy. According to the obtained results, exergy destruction of boiler, turbine, and condenser at full load and half load are the highest, respectively. Also, Ahmadi et al. [5] found that the boiler is the main source of wasting exergy in the Isfahan steam power plant.

Despite the extensive studies on CEAM, this method does not count the avoidable irreversibilities and does not pay attention to the precise interactions between components [6]. The advanced exergy analysis method (AEAM) determines how much of the exergy destruction achieved by the CEAM can be avoided and also determines how much of the exergy destruction in a component is caused by the inefficiencies of other components [7]. This idea was firstly introduced by Tsatsaronis and his co-workers [8, 9]. Nowadays, the AEAM is well implemented in various systems. Liao et al. [10] analyzed exhaust gas heat recovery in ORC based combined systems and using AEAM, they concluded that 25.65% of total exergy destruction is avoidable. Ozcan et al. [11] simulated a solar PV-air source heat pump with a battery system. AEAM results revealed that all sections of the batteries’ exergy destruction are significant. The results of AEAM on an absorption-ejection refrigeration cycle by Chen et al. [12] indicated that generator and absorber have the first and second order of optimization priority, because those have the most avoidable exergy destruction. Wang et al. [13] analyzed the exergetic performance of the dual-loop ORC used in engine waste heat recovery. The CEAM results point out that, the most exergy destruction occurs in the high-temperature evaporator. In contrast, in AEAM, the priority for optimization is given to the low-temperature turbine. Wang et al. [14] also evaluated the performance of a dual-loop ORC with a zeotropic mixture according to the AEAM. They found that the high-temperature turbine is the first component that should be repaired. Also, Liu et al. [15] assessed a transcritical CO2 ejector refrigeration system integrated with a thermoelectric sub-cooler. The outcomes of AEAM revealed that the avoidable exergy destruction of compressor is the largest, which differs from the outcomes of CEAM. Ebrahimi et al. [16] examined the Island underwater compressed air energy storage plant. The outcomes of CEAM indicated that the first optimization priority belongs to the turbine. Whereas, using the AEAM, one of the heat exchangers has the highest priority for optimization. Oyekale et al. [17] conducted advanced exergoeconomic method on a hybrid solar-biomass ORC plant and found that 60% of irreversibility cost rates can be avoided. The advanced exergy, exergeonomic, and exergoenvironmental analyses on a heat pump aimed at space heating were studied by Voloshchuk et al. [18]. They reported that annual exergy destruction, annual cost of exergy of the product, and annual environmental impact are reduced by improving system performance.

The Kalina cycle is one of the cycles used to generate electricity from low-temperature geothermal heat sources, which was first proposed by Alexander Kalina in 1984 [19]. Worldwide, only one plant based on KSC-34 principles has been built in Husavik, Iceland, with an installed capacity of 2 MW [20]. Some studies have examined the Kalina cycle based on AEAM. Using AEAM, Fallah et al. [21] concluded that the improvement priority belongs to the condenser, turbine, and evaporator in the Kalina cycle, respectively. Whereas, in the
CEAM, improvement priority is given to the condenser, evaporator, and turbine, respectively. AEAM shows that the auxiliary heater and Parabolic-Trough Solar Collectors (PTSC) have the highest improvement priority in a Kalina cycle integrated with PTSC, as reported by Boyaghchi and Sabaghian [22].

Although the AEAM improves the outcomes of CEAM, it has some weaknesses as follows: a) The subjectivity that is associated with the definition of hybrid and ideal processes, b) the significant number of simulations and calculations that are required to achieve different parts of exergy destruction [23]. Therefore, due to the many calculations and complexity of the solution process in the AEAM, the probability of error in calculations increases and sometimes the outputs of AEAM are not easily evaluated.

This paper presents a novel analysis method called the extended thermodynamic analysis method (ETAM) that covers the weaknesses of AEAM. ETAM is less complicated than the AEAM (There is no need to define ideal and hybrid processes). Therefore, the probability of error in calculations is reduced. Whereas, the outcomes of ETAM and the AEAM are similar for determining the improvement priority of components. Generally, ETAM is composed of three sub-methods, including extended energy analysis, extended entropy analysis, and extended exergy analysis. Therefore, the system is examined from three viewpoints of energy, entropy, and exergy, whose their results are confirmed by each other. In this study, a Kalina cycle system-34 (KCS-34) is considered to produce power from low-temperature geothermal sources. KCS-34 is firstly investigated using the CEAM and AEAM and then by ETAM. Finally, the results of CEAM, AEAM, and ETAM are compared with each other to find the best strategy for the improvement of KCS-34 performance.

2. System configuration and assumptions

Kalina power cycles have different configurations based on the cycle applications. KCS-34 is one of the most used cycles for power generation from geothermal energy. The working fluid of all Kalina cycles is ammonia-water mixture with different boiling and condensation points at constant pressure [24]. So the heat source (sink source) and the working fluid can have a better heat matching in the evaporator (condenser), which improves the performance of the Kalina cycle [25]. A schematic view of the KCS-34 is shown in Fig. 1. The main components of a KCS-34 are a turbine, a generator, an evaporator, a separator, a low-temperature recuperator (LTR), a high-temperature recuperator (HTR), a condenser, a pump, an expansion valve, and a Mixer. In KCS-34, the ammonia-water mixture absorbs heat from the heat source in the evaporator (s8→s9) and the hot two-phase flow enters a separator. Then, the rich ammonia vapor from poor ammonia liquid (s9→s10, s9→s1) is separated. The rich ammonia flow goes to the turbine for power generation (s1→s2) and then enters the mixer. The poor ammonia liquid, after passing the HTR and expansion valve, is mixed with turbine outlet flow (s2, s12→s3). After it, the ammonia-water mixture flows into LTR and eventually, the condensed liquid at the
condenser outlet is pumped to the maximum pressure of the cycle. Then, the pumped mixture is pre-heated by passing through LTR and HTR and is sent into the evaporator (s6→s7→s8), and all processes start again [20].

The inlet parameters used for simulating the KSC-34 performance are listed in Table 1.

To simulate the system, general assumptions are considered as follows [27–29].

- The system works in steady-state conditions.
- The variations in potential and kinetic energies are neglected.
- Specified isentropic efficiencies are considered for pump, turbine, and generator.
- The vapor and liquid flows at separator outlet are considered saturated vapor and saturated liquid, respectively.
- The condenser outlet flow is assumed to be a saturated liquid.

### 3. Thermodynamic modeling

#### 3.1. Energy analysis and CEAM

The equations of mass, energy and exergy for each control volume is expressed as follows:

\[
\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (1)
\]

\[
\dot{Q} - \dot{W} = \sum_{out} \dot{m} h - \sum_{in} \dot{m} h \quad (2)
\]

\[
\dot{E}_Q - \dot{W} = \sum_{out} \dot{m} \varphi - \sum_{in} \dot{m} \varphi + \dot{E}_d \quad (3)
\]

where \( \sum_{in} \dot{m} h \) and \( \sum_{out} \dot{m} h \) indicate the energy transfer by mass flowing into or out of the control volume, respectively, \( \sum_{in} \dot{m} \varphi \) is the input flow exergy, \( \sum_{out} \dot{m} \varphi \) is the output flow exergy.

The \( \dot{E}_Q \) can be written as follows:

\[
\dot{E}_Q = \sum_j (1 - T_0 / T_j) \dot{Q}_j \quad (4)
\]

where \( \dot{Q}_j \) is the heat transferred out of the system boundaries, \( T_j \) is instantaneous temperature and \( T_0 \) is ambient temperature.

The flow exergy (\( \dot{\Psi} \)) can be divided into chemical exergy (\( \dot{\Psi}^{CH} \)), physical exergy (\( \dot{\Psi}^{PH} \)), potential exergy (\( \dot{\Psi}^{PT} \)) and kinetic exergy (\( \dot{\Psi}^{KN} \)). As assumed earlier, the variations in potential and kinetic energy are considered negligible and therefore, the exergy of flow \( j \) can be written as sum of chemical and physical exergy [30]:

\[ \dot{\Psi}_j = \dot{\Psi}_j^{CH} + \dot{\Psi}_j^{PH} \]
\[
\Psi_j = \Psi_{CH}^j + \Psi_{PH}^j
\]  
(5)

The physical exergy of flow \(j\) can be computed as following equation:

\[
\Psi_{PH}^j = m \dot{\psi}_{PH}^j = m \left[ (h_j - h_0) - T_0 (s_j - s_0) \right]
\]  
(6)

Since the concentration of ammonia in Kalina cycle changes, as a result, the variations in chemical exergy should be considered. The chemical exergy of flow \(j\) can be obtained using following equation [31]:

\[
\Psi_{CH}^j = m \dot{\psi}_{CH}^j = m \left[ \left( \frac{\psi_{0,CH}^{NH_3}}{M_{NH_3}} \right) x_j + \left( \frac{\psi_{0,CH}^{H_2O}}{M_{H_2O}} \right) (x_j - 1) \right]
\]  
(7)

In above equation, \(\psi_{0,CH}^{NH_3}\) and \(\psi_{0,CH}^{H_2O}\) are the standard molar specific chemical exergy of water and ammonia, and \(M_{H_2O}\) and \(M_{NH_3}\) are molecular weight of water and ammonia, respectively [32].

The exergy balance for each system component (k) can be represented as follows:

\[
\dot{E}_{P,k} = \dot{E}_{F,k} - \dot{E}_{d,k}
\]  
(8)

where \(\dot{E}_{P,k}\), \(\dot{E}_{F,k}\) and \(\dot{E}_{d,k}\) are the product exergy, fuel exergy and exergy destruction for kth component, respectively [33]. The exergy balance for the whole system is stated as [34]:

\[
\dot{E}_{P,\text{tot}} = \dot{E}_{F,\text{tot}} - \dot{E}_{d,\text{tot}} - \dot{E}_L = \dot{E}_{F,\text{tot}} - \dot{E}_w
\]  
(9)

where \(\dot{E}_L\) is the exergy loss of the whole system and it is associated with the transfer of exergy through material and energy streams to the surroundings, \(\dot{E}_{d,\text{tot}}\) is total exergy destruction and it is associated with the irreversibilities within the system boundaries, and \(\dot{E}_w\) s wasted exergy which is sum of the exergy loss and total exergy destruction. Moreover, Eqs. (10)-(13) are used to obtain the parameters required for evaluation of system performance.

\[
\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{d,k}}{\dot{E}_{F,k}}
\]  
(10)

\[
\eta_{\text{exergy}} = \frac{\dot{E}_{P,\text{tot}}}{\dot{E}_{F,\text{tot}}} = \frac{W_{\text{net}}}{E_m}
\]  
(11)

\[
y_k = \frac{\dot{E}_{d,k}}{\dot{E}_{F,k}} \times 100
\]  
(12)

\[
y^*_k = \frac{\dot{E}_{d,k}}{\dot{E}_{d,\text{tot}}} \times 100
\]  
(13)
In above equations, $\varepsilon_k$, $\eta_{\text{exergy}}$, $y_k$ and $y_k^*$ are exergy efficiency of $k$th component, total exergy efficiency, exergy destruction ratio and relative exergy destruction, respectively. In addition, in Eq. (11), total product exergy is net output work of system and total fuel exergy is input exergy to evaporator through heat transfer of geothermal working fluid. Table 2 lists the fuel and product exergies for the KCS-34 components.

3.2 AEAM

AEAM examines the interdependence between exergy destructions of components and the actual amount of component improvement priority [23]. In this method, the exergy destruction which is an important parameter for analysis of the energy systems, can be divided into exogenous/endogenous and unavoidable/avoidable sections.

The endogenous exergy destruction for a component ($\dot{E}_{d,k}^{EN}$) can be achieved when it works in real conditions while other components work in ideal conditions. The exogenous exergy destruction ($\dot{E}_{d,k}^{EX}$) can be obtained by subtracting the endogenous exergy destruction from the exergy destruction.

$$\dot{E}_{d,k} = \dot{E}_{d,k}^{EN} - \dot{E}_{d,k}^{EX}$$  \hspace{1cm} (14)

The endogenous exergy destruction rate for $k$th component is written as [35]:

$$\dot{E}_{d,k}^{EN} = \dot{E}_{P,k}^{EN} \left( \frac{\dot{E}_{d,k}}{\dot{E}_{P,k}} \right)^{EN}$$  \hspace{1cm} (15)

where $\left( \dot{E}_{d,k} / \dot{E}_{P,k} \right)^{EN}$ is defined as exergy destruction to product exergy for $k$th component in hybrid cycle.

Different methods are currently available to calculate $\dot{E}_{d,k}^{EN}$. In this research, the thermodynamic cycle method is used to obtain the $\dot{E}_{d,k}^{EN}$, that the accuracy of this method has been demonstrated by Kelly et al. [34]. This method is the most suitable method for systems operate based on a thermodynamic cycle [36].

The unavoidable exergy destruction ($\dot{E}_{d,k}^{UN}$) is a section of the component exergy destruction which cannot be eliminated due to technical limitations like accessibility, material cost and production methods. Furthermore, the avoidable exergy destruction ($\dot{E}_{d,k}^{AV}$) can be achieved by subtracting the unavoidable exergy destruction from exergy destruction.

$$\dot{E}_{d,k} = \dot{E}_{d,k}^{UN} - \dot{E}_{d,k}^{AV}$$  \hspace{1cm} (16)
In order to account the unavoidable exergy destruction of a component, the exergy efficiency of that component should be maximized. Under unavoidable conditions, the irreversibilities are minimized and only the unavoidable irreversibilities remains.

When a system is operating in an unavoidable conditions, the unavoidable exergy destruction can be expressed as [30]:

\[
\dot{E}^{\text{UN}}_{d,k} = \dot{E}_{p,k} \left( \frac{\dot{E}_{d,k}}{\dot{E}_{p,k}} \right)^{\text{UN}}
\]

Where \( (\dot{E}_{d,k} / \dot{E}_{p,k})^{\text{UN}} \) is ratio of exergy destruction to product exergy for kth component in unavoidable conditions.

By combining the endogenous, exogenous, avoidable and unavoidable exergy destructions for kth component, it can be written that the sum of four exergy destruction sections are equal to conventional exergy destruction.

\[
\dot{E}_{d,k} = \dot{E}^{\text{EN,AV}}_{d,k} + \dot{E}^{\text{EN,UN}}_{d,k} + \dot{E}^{\text{EX,AV}}_{d,k} + \dot{E}^{\text{EX,UN}}_{d,k}
\]

Where \( \dot{E}^{\text{EN,AV}}_{d,k} \) is avoidable endogenous exergy destruction, which is decreased through improving the performance of kth component and \( \dot{E}^{\text{EN,UN}}_{d,k} \) is unavoidable endogenous exergy destruction, which cannot be decreased due to technological limitations of kth component. \( \dot{E}^{\text{EX,AV}}_{d,k} \) is avoidable exogenous exergy destruction, which can be decreased through improving the performance of other components and \( \dot{E}^{\text{EX,UN}}_{d,k} \) is unavoidable exogenous exergy destruction, which cannot be decreased due to technical limitations of the other components [37]. The various sections of the \( \dot{E}_{d,k} \) can be achieved using Eqs. (19)-(22).

\[
\dot{E}^{\text{EN,UN}}_{d,k} = \dot{E}^{\text{EN}}_{p,k} \left( \frac{\dot{E}_{d,k}}{\dot{E}_{p,k}} \right)^{\text{UN}}
\]

\[
\dot{E}^{\text{EX,UN}}_{d,k} = \dot{E}_{d,k} - \dot{E}^{\text{EN,UN}}_{d,k}
\]

\[
\dot{E}^{\text{EN,AV}}_{d,k} = \dot{E}^{\text{EN}}_{d,k} - \dot{E}^{\text{EN,UN}}_{d,k}
\]

\[
\dot{E}^{\text{EX,AV}}_{d,k} = \dot{E}^{\text{EX}}_{d,k} - \dot{E}^{\text{EX,UN}}_{d,k}
\]

where \( \dot{E}^{\text{EN}}_{d,k} \) is endogenous product exergy for kth component.

Ideal, real, hybrid and unavoidable cycles are simulated to find the various sections of the exergy destruction. In ideal cycle, all processes are assumed reversible while in real cycle they are irreversible. In a hybrid cycle, the
kth component operates in real conditions and other components operate in ideal conditions, to calculate $\dot{E}_{d,k}^{EN}$. The number of hybrid conditions is equal to the number of components [37]. The $\dot{E}_{d,k}^{UN}$ can be obtained using unavoidable cycle in which all components operates under unavoidable conditions. In unavoidable conditions, the improvement priority for system components is maximized despite technical limitations.

The improvement potential of each component can be obtained by dividing the avoidable exergy destruction of the component by its conventional exergy destruction [38].

$$IP_k = \frac{\dot{E}_{d,k}^{AV}}{\dot{E}_{d,k}}$$

(23)

The assumptions required to analyze KCS-34 in the real, ideal and unavoidable conditions are listed in Table 3, respectively. In this table, $\Delta T_{\text{min}}$ is minimum temperature difference, $\Delta T_{pp}$ is pinch point temperature difference and $\Delta P$ demonstrates the pressure drop in flows. Also, for analysis of ideal Kalina cycle, an isentropic expander is provided instead of expansion valve because the throttling process is irreversible.

It is noteworthy that, the amount of net output power in the ideal and hybrid conditions ($\dot{W}_{\text{net,ideal}}, \dot{W}_{\text{net,hybrid}}$) are considered constant and equal to the net output power in real conditions ($\dot{W}_{\text{net,real}}$).

### 3.3 ETAM

As discussed, KCS-34 is investigated using a novel analysis method named ETAM in this study. ETAM is composed of 3 parts and each part can evaluate the system performance individually. These 3 parts are extended energy analysis, extended entropy analysis and extended exergy analysis.

For each of the extended analyses, the Kalina cycle is simulated in both the real operating conditions and the reference operating conditions. Under the real conditions, both unavoidable and avoidable irreversibilities are considered for all of the system components (real cycle). In the reference conditions, the avoidable irreversibilities of a system component (e.g. kth component) are avoided, while the unavoidable irreversibilities of the component remain, and other components operate under their real conditions (reference conditions for kth component). In other words, in reference conditions, the kth component operates in unavoidable conditions while the rest of components operate in real conditions. This process will be performed for each component in the system. Therefore, it can be said that the number of simulated cycles under the reference conditions (reference cycles) is equal to the number of the system components.

In extended energy analysis, using energy balance equation (Eq. (2)), the following equation can be obtained.
\[ W_{net,ref_k} = W_{Gen,ref_k} - W_{pump,ref_k} \]  

where \( W_{net,ref_k}, W_{Gen,ref_k}, \) and \( W_{pump,ref_k} \) are net output power, generator power generation and pump power consumption, under the reference conditions for kth component, respectively. It is clear that the improvement priority is given to the component that creates the most net output power under the reference conditions.

The entropy balance equation is used for extended entropy analysis over a control volume which is written as follow [45]:

\[ \sum \frac{\dot{Q}_j}{T_j} = \sum_{\text{out}} \dot{m}_s - \sum_{\text{in}} \dot{m}_s - \dot{S}_{gen} \]

where \( \sum \dot{Q}_j/T_j \) is sum of the entropy transfer rates due to heat transfer, \( \sum_{\text{out}} \dot{m}_s \) and \( \sum_{\text{in}} \dot{m}_s \) are entropy transfer by mass flowing into or out of the control volume, respectively and \( \dot{S}_{gen} \) is the entropy generation in control volume. In extended entropy analysis, the total entropy generation is calculated under the reference conditions (\( \dot{S}_{gen,tot,ref} \)). The improvement priority is given to the component that in reference conditions leads to minimum total entropy generation.

In extended exergy analysis, the wasted exergy is calculated using exergy balance equation for overall system (Eq. (9)) under the reference conditions (\( \dot{E}_{w,ref} \)). Then, the improvement priority is given to the component that under the reference conditions leads to minimum wasted exergy.

The energy and entropy balances for the KSC-34 components are summarized in Table 4. In this table, \( \eta_{is} \) is isentropic efficiency and \( x \) is the concentration of ammonia. Furthermore, subscripts \( ra, pa, gf \) and \( cw \) denotes rich ammonia flow, poor ammonia flow, geofluid and cooling water.

4. Results and discussion

4.1. Validation of the model

The data reported by Fallah et al. [21] are used to validate the outcomes of the model proposed in this study. Fallah et al. [21] implemented CEAM and AEAM on a Kalina cycle used in enhanced geothermal power plant. Table 5 compares the thermodynamic data and mass flow rate results, and Fig. 2 compares the different sections of exergy destruction for Kalina cycle components. As presented in Table 4 and Fig. 2, Comparison of the outcomes shows that the data obtained in the current study and the data reported by Fallah et al. [21] are in agreement. After validation of the presented model, the Kalina cycle is evaluated using the proposed novel method called ETAM.
4.2. Energy analysis and CEAM

Table 6 indicates the thermodynamic properties for different state points of KCS-34 in real, ideal and unavoidable conditions, respectively. In addition, the values obtained for turbine power, pump power, net output power, energy efficiency and total exergy efficiency are indicated in Table 7. Given that the $\dot{W}_{\text{net}}$ of ideal cycle is assumed equal to $\dot{W}_{\text{net}}$ of real cycle, so the mass flow rate of the ideal cycle will be less than that of real cycle. Thus, although the difference between input and output specific enthalpies of the turbine in the ideal cycle is larger than the real cycle, but the turbine power in the ideal cycle is less. It is the same for unavoidable cycle.

The outcomes of CEAM on KCS-34 at real, ideal and unavoidable conditions are given in Tables 8-10, respectively. In CEAM, the improvement priority is given to components with greater exergy destruction. According to Table 8, the maximum exergy destruction in real conditions belong to the condenser, followed by the evaporator, turbine, LTR and HTR, while the pump has the lowest exergy destruction.

4.3. AEAM

The process of calculating the exergy destructions for kth component and corresponding equations are shown in flowchart of Fig. 3.

The outcomes of AEAM of the KCS-34 are listed in Table 11. By dividing the exergy destruction into exogenous and endogenous parts (second and third columns of Table 11), following outcomes are obtained:

- In investigated components, $\hat{D}^{\text{EN}}_{d,k}$ is greater than $\hat{D}^{\text{EX}}_{d,k}$. It means that the highest exergy destruction of each component is caused by the internal irreversibility of the component itself. Thus, the interdependence between the components is not strong.

- The $\hat{D}^{\text{EX}}_{d,k}$ in condenser is 119.9 kW which is 31.98% of the total exogenous exergy destruction ($\hat{D}^{\text{EX}}_{d,\text{tot}}$), followed by LTR (115.7kW) and evaporator (104.5kW). Therefore, the improvement of the remaining components can significantly reduce the exergy destruction of these three components.

To assess the real potential for component improvement, the exergy destruction is also divided into avoidable and unavoidable parts (fourth and fifth columns of Table 11) and the following conclusions are found:

- The value of $\hat{D}^{\text{AV}}_{d,k}$ in condenser and LTR is much greater than $\hat{D}^{\text{UN}}_{d,k}$. This shows that these two components can be significantly modified using technological enhancement.

- The highest $\hat{D}^{\text{AV}}_{d,k}$ belongs to condenser, followed by LTR, turbine and evaporator, which account together for 89.96% (916.23 kW) of total avoidable exergy destruction.
- In evaporator, HTR, and expansion valve, the $\dot{E}_{UN,d,k}^{AV}$ is greater than $\dot{E}_{d,k}^{AV}$. It implies that improvement of these components has no remarkable impact on improving the system efficiency.
- In the studied cycle, up to 1018.49 kW or 66.22% of total exergy destruction can be avoided and hence, the system has high potential for efficiency improvement.

Considering the combination of exogenous/endogenous and unavoidable/avoidable exergy destruction, it can be divided into four sections (sixth to ninth columns of Table 1). As revealed, in most of the components, $\dot{E}_{d,k}^{AV}$ is greater than $\dot{E}_{d,k}^{UN}$ which means that the improvement of that component can reduce the exergy destruction in that component and other system components. Therefore, $\dot{E}_{d,k}^{EX,AV}$ and $\dot{E}_{d,k}^{EN,AV}$ should be considered. It is concluded that:

- The highest $\dot{E}_{d,k}^{EX,AV}$ belongs to the condenser, followed by LTR and then evaporator. This shows that the efficiency improvement of other components has higher effect on reduction of exergy destruction in these three components.
- The highest $\dot{E}_{d,k}^{EN,AV}$ belong to condenser, followed by turbine and LTR, which account together for 77.24% (524.65 kW) of total avoidable endogenous exergy destruction ($\dot{E}_{d,\text{tot}}^{EN,AV}$). Technical improvement of these components can significantly reduce the total exergy destruction and increase the system efficiency.
- Improvement of a component with higher $\dot{E}_{d,k}^{EN,AV}$ can have substantial effect on reduction of system exergy destruction without any impact on exergy destruction of the other components. AEAM suggests that the first priority of improvement should be given to the condenser because it accounts for 29.88% of $\dot{E}_{d,\text{tot}}^{EN,AV}$, followed by turbine, LTR, evaporator, generator and pump.
- IP parameter can be used to identify the improvement potential of each component [46]. According to the last column of Table 1, the condenser has the highest IP value, so after improving the system, 90.65% of condenser exergy destruction can be avoided, followed by LTR, pump, generator and turbine. Also, the IP for the whole system is determined to be 66.22%, which shows that the system has significant potential for improvement. In some studies, IP parameter is used to prioritize components [36].
- The avoidable endogenous exergy destruction of HTR ($\dot{E}_{d,HTR}^{EN,AV}$) is negative. Because $\dot{E}_{d,HTR}^{EN,UN} > \dot{E}_{d,HTR}^{EN}$ and hence, it can be inferred that $\dot{E}_{d,HTR}^{EN,AV} < 0$. The negative sign indicates that the increase in the HTR irreversibilities leads to a decrease in $\dot{E}_{d,HTR}^{EN,AV}$. In fact, when HTR irreversibilities are increased, both
product and fuel exergies are increased, so that their difference (i.e., HTR exergy destruction) is decreased [47].

4.4. ETAM

As discussed, the AEAM enhances the accuracy of exergy analysis. But among its weaknesses are high number of required simulations and complexity of the solving procedure. For this reason, in this research a novel analysis called ETAM is proposed. This novel method is easier than AEAM, while the outcomes of both methods are similar for determining the improvement priority of components.

ETAM is used in this study to investigate the low-temperature geothermal source driven-KCS-34. In ETAM, KCS-34 is simulated under reference conditions. In reference conditions, a component works in unavoidable conditions and the rest of components work in real conditions. Thus the number of reference conditions is equal to the number of system components.

The objective function is selected based on the type of the system (power generation, heat generation and so on). In extended energy analysis, for KCS-34 as a power generation cycle, the net output power is taken into account as objective function. The improvement priority is given to the component that under the reference conditions, leads to highest net output power. In extended entropy analysis, the total entropy generation is considered as the objective function and the improvement priority is given to the component that under the reference conditions, leads to lowest total entropy generation in the whole cycle. Also in extended exergy analysis, the wasted exergy of the system is calculated as the objective function. Here, the improvement priority is given to the component that under the reference conditions, minimizes the wasted exergy.

The results obtained from ETAM is presented in Table 12. This table lists the amount of net output power, total entropy generation and wasted exergy under the reference and real conditions. Also, the improvement percentage of these parameters is shown in Fig. 3. As seen in Fig. 4, in the reference conditions for HTR (ie when HTR works under unavoidable conditions and the rest of the components work in real conditions), the improvement percentage of $\dot{W}_{net,ref_{HTR}}$, $\dot{S}_{gen,tot,ref_{HTR}}$ and $\dot{E}_{w,ref_{HTR}}$ are negative. It means that by improving HTR, the net output power decreases while the total entropy generation and wasted exergy increase. According to Eq. (9), after subjecting HTR to reference conditions, it is observed that $\dot{E}_{d,HTR}$ and as a result, $\dot{E}_{d,tot}$ decrease, but $\dot{E}_{L}$ increases which leads to increase in wasted exergy. Regarding the net output power, the pressure ratio of the turbine increases with the improvement of HTR, while the mass flow rate of the system decreases, also the difference of enthalpies in the turbine and in the pump does not change much. Therefore, the powers of the turbine and pump are reduced so that this reduces the net output power. Also, the decrease in the mass flow rate causes an increase in total entropy generation.
According to Fig. 4, the priority of components for improvement using extended energy, entropy and exergy analyses is similar. For instance, when condenser is under the reference conditions, the highest improvement percentage of 13.5%, 11.05% and 10.86% are obtained for $\dot{W}_{\text{net,refCond}}$, $\dot{S}_{\text{gen,tot,refCond}}$ and $\dot{E}_{\text{w,refCond}}$, respectively. Therefore, the condenser is considered as first priority for improvement; while expansion valve and HTR are not included. Obviously, three parts of the extended analyses leads to the same improvement priority. Then it is concluded that, the calculations of the model are correctly performed.

**4.5. Comparison of CEAM, AEAM and ETAM**

As mentioned earlier, in CEAM, the improvement priority is related to the component with the highest exergy destruction while in AEAM, the priority belongs to the component with the highest $E_{d}^{\text{EN,AV}}$. Moreover, in ETAM, the improvement priority is given to the component that in its reference condition leads to highest improvement in $\dot{W}_{\text{net,ref}}$, $\dot{S}_{\text{gen,tot,ref}}$ and $\dot{E}_{\text{w,ref}}$. Based on the results presented in Tables 8, 11 and 12, the improvement priority for KCS-34 components is shown in Fig. 5 (The bigger the number, the less priority for optimization.) and following findings are obtained:

- Using CEAM and AEAM, different improvement priority are achieved for components. For example, in CEAM the most irreversibilities occur in condenser and evaporator, respectively, due to the two-phase transition processes. Therefore the first and second improvement priority is given to these two components. While in AEAM, the evaporator has the fourth order of improvement priority. Because a large section of the exergy destruction in the evaporator is unavoidable.
- The results obtained using 3 parts of ETAM (including extended energy, extended entropy, and extended exergy analyses) are confirmed each other.
- Comparing the outcomes of AEAM and ETAM, it is found that the improvement priority of the system components are similar in both methods while ETAM is clearly easier and also it is a self-validated method.

**5. Conclusions**

This paper presents a novel extended thermodynamic analysis method called ETAM to better evaluation of the thermodynamic cycles. This method introduces the best strategy for determining the improvement priority of components compared to CEAM and AEAM. ETAM is more accurate than the CEAM and less complex than the AEAM. It is composed of three different parts, including extended energy analysis, extended entropy analysis and extended exergy analysis. Then after total analysis, the results of different parts confirm each other and consequently, ETAM is a self-validated method.
To investigate ETAM, this method is used to evaluate a low-temperature geothermal Kalina cycle system-34 and the priority of components improvement is determined and compared with the outputs of CEAM and AEAM. The main conclusions are as follows:

- Using part I: extended energy analysis, the improvement priority of components is given to condenser, turbine, and LTR, respectively. Because by subjecting these three components to reference conditions, the highest net output power with values of the 2428 kW, 2344 kW and 2276 kW is created for the system, respectively.
- In Part II: extended entropy analysis, by subjecting condenser, turbine, and LTR to reference conditions, the lowest total entropy generation with values of the 7.594 kW/K, 7.828 kW/K and 8.014 kW/K are obtained for the system, respectively. Hence the improvement priority is given to these components, again.
- Part III: Extended exergy analysis indicates that the lowest wasted exergy occurs in condenser, turbine, and LTR with values of the 2412 kW, 2503 kW and 2580 kW, under the reference conditions. Therefore, the first, second, and third priority of improvement belongs to these three components, respectively.
- For situations where no validation is required, one of the three parts of ETAM is sufficient to determine components improvement priority. But when evaluation and validation of results are required, two or three parts of ETAM can be performed. The results obtained using three parts of ETAM are confirmed each other and hence ETAM validates itself automatically.
- According to the CEAM, the most exergy destruction belongs to the condenser, evaporator, and turbine, respectively. However, using AEAM, the improvement priority of components is given to condenser, turbine, and LTR, respectively, due to higher avoidable endogenous exergy destruction. This difference in improvement priority is because the AEAM considers the interdependence between components and real potential for components improvement.
- By comparing the outcomes of ETAM and AEAM, it can be concluded the improvement priority of the system components is similar in both methods. But in advanced exergy analysis, the complexity of the solution and the number of simulations required to obtain different sections of exergy destruction is much greater than ETAM.

Nomenclature

Symbols

\[ \dot{E} \quad \text{Exergy (kW)} \]
\[ h \quad \text{Specific enthalpy (kJ/kg)} \]
\[ M \quad \text{Molar} \]
\[ \dot{m} \quad \text{Mass flow rate (kg/s)} \]
\[ P \quad \text{Pressure (bar)} \]
\[ \dot{Q} \quad \text{Heat transfer rate (kW)} \]
\[ Qu \quad \text{Quality} \]
\[ s \quad \text{Specific entropy (kJ/Kg.K)} \]
\[ \dot{S} \quad \text{Entropy (kW/K)} \]
\[ T \quad \text{Temperature (K)} \]
\[ \dot{W} \quad \text{Power (kW)} \]
\[ x \quad \text{Ammonia concentration} \]

**Abbreviations**

- HTR: High temperature recuperator
- LTR: Low temperature recuperator

**Subscripts**

- Cond: Condenser
- cw: Cooling water
- d: Destruction
- Evap: Evaporator
- EXV: Expansion valve
- F: Fuel
- Gen: Generation
- Gene: Generator
- gf: Geothermal fluid
- in: Inlet
- is: Isentropic
- k: Component
- L: Loss
- min: Minimum
- Mix: Mixer
- out: Outlet
- P: Product
- pa: Poor ammonia flow
- pp: Pinch point
Q \quad \text{Heat transfer}
ra \quad \text{Rich ammonia flow}
ref \quad \text{Reference condition}
Sep \quad \text{Separator}
tot \quad \text{total}
Turb \quad \text{Turbine}
1, 2, \ldots \quad \text{Flow number}
0 \quad \text{Reference state}

\textit{Superscripts}

\begin{align*}
AV & \quad \text{Avoidable} \\
CH & \quad \text{Chemical} \\
EN & \quad \text{Endogenous} \\
EX & \quad \text{Exogenous} \\
KN & \quad \text{Kinetic} \\
PH & \quad \text{Physical} \\
PN & \quad \text{Potential} \\
UN & \quad \text{Unavoidable} \\
0 & \quad \text{Standard state}
\end{align*}

\textit{Greek symbols}

\begin{align*}
\eta & \quad \text{Efficiency} \\
\varepsilon & \quad \text{Exergy efficiency} \\
\psi & \quad \text{Specific exergy flow (kJ/kg)} \\
\dot{\psi} & \quad \text{Exergy flow (kW)}
\end{align*}

\textbf{References}


prove energy, ing zeotropic mixture”


**Tables’ Captions:**

Table 1. Inlet parameters for KSC-34 simulation [26].

Table 2. Definition of fuel exergy and product exergy for KCS-34 components.

Table 3. Assumptions for the KCS-34 simulation under real, ideal and unavoidable conditions.

Table 4. Thermodynamic equations for the KSC-34 components.

Table 5. Details of the model validation using the data reported by Fallah [21].

Table 6. Thermodynamic parameters of KCS-34 in real, ideal, and unavoidable conditions.

Table 7. The results of energy analysis.

Table 8. CEAM results on KCS-34 under real conditions.

Table 9. CEAM results on KCS-34 under ideal conditions.
Table 10. CEAM results on KCS-34 under unavoidable conditions.

Table 11. Results of AEAM.

Table 12. Results of extended thermodynamic analysis.

**Figures’ Captions:**

Fig. 1. Schematic diagram of the KCS-34.

Fig. 2. Comparison of the exergy destruction of a) endogenous and exogenous, b) avoidable and unavoidable, and c) conventional of obtained in present study and those reported in Ref. [21].

Fig. 3. Flowchart of calculating the exergy destructions for the kth component (conventional and advanced).

Fig. 4. Improvement percentage of net output power, total entropy generation and wasted exergy for different components under the reference conditions.

Fig. 5. Improvement priority of components in KCS-34.
Table 1. Inlet parameters for KSC-34 simulation [26].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>kg NH$_3$/kg solution</td>
<td>0.82</td>
</tr>
<tr>
<td>$\dot{m}_{gf}$</td>
<td>kg/s</td>
<td>89</td>
</tr>
<tr>
<td>$T_{gf, in}$</td>
<td>°C</td>
<td>122</td>
</tr>
<tr>
<td>$P_{gf, in}$</td>
<td>bar</td>
<td>2.5</td>
</tr>
<tr>
<td>$P_{gf, out}$</td>
<td>bar</td>
<td>2.5</td>
</tr>
<tr>
<td>$T_{15}$</td>
<td>°C</td>
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<tr>
<td>$T_{16}$</td>
<td>°C</td>
<td>18</td>
</tr>
<tr>
<td>$P_{15}$</td>
<td>bar</td>
<td>1.2</td>
</tr>
<tr>
<td>$P_{16}$</td>
<td>bar</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 2. Definition of fuel exergy and product exergy for KCS-34 components.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{E}_{F,k}$</th>
<th>$\dot{E}_{P,k}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>$\Psi_1 - \Psi_2$</td>
<td>$\Psi_{Turb}$</td>
</tr>
<tr>
<td>Pump</td>
<td>$\dot{W}_{Pump}$</td>
<td>$\Psi_6 - \Psi_5$</td>
</tr>
<tr>
<td>LTR</td>
<td>$\Psi_3 - \Psi_4$</td>
<td>$\Psi_7 - \Psi_6$</td>
</tr>
<tr>
<td>HTR</td>
<td>$\Psi_{10} - \Psi_{11}$</td>
<td>$\Psi_8 - \Psi_7$</td>
</tr>
<tr>
<td>Evaporator</td>
<td>$\Psi_{13} - \Psi_{14}$</td>
<td>$\Psi_9 - \Psi_8$</td>
</tr>
<tr>
<td>Condenser</td>
<td>$\Psi_{4} - \Psi_{5}$</td>
<td>$\Psi_{16} - \Psi_{15}$</td>
</tr>
<tr>
<td>Separator</td>
<td>$\Psi_9$</td>
<td>$\Psi_1 + \Psi_{10}$</td>
</tr>
<tr>
<td>Mixer</td>
<td>$\Psi_2 + \Psi_{12}$</td>
<td>$\Psi_3$</td>
</tr>
<tr>
<td>expansion valve</td>
<td>$\Psi_{11} - \Psi_{12}$</td>
<td>$\dot{m}<em>{11} (h</em>{11} - h_{12})$</td>
</tr>
</tbody>
</table>
Table 3. Assumptions for the KCS-34 simulation under real, ideal and unavoidable conditions.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Real</th>
<th>Ideal</th>
<th>Unavoidable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser</td>
<td>$\Delta T_{\text{min}}$</td>
<td>3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>0.5&lt;sup&gt;c, d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>$\Delta P_{4,5}$</td>
<td>17.33%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>1%</td>
</tr>
<tr>
<td>LTR</td>
<td>$\Delta T_{\text{min}}$</td>
<td>5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>0.5&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>$\Delta P_{3,4}$</td>
<td>15.2%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>1%&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>HTR</td>
<td>$\Delta T_{\text{min}}$</td>
<td>5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>0.5&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>$\Delta P_{7,8}$</td>
<td>2.9%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>1%&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>$\Delta P_{10,11}$</td>
<td>3.1%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>1%&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Evaporator</td>
<td>$\Delta T_{\text{min}}$</td>
<td>6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>0.5&lt;sup&gt;c, d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>$\Delta P_{8,9}$</td>
<td>3%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>1%&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>$\Delta T_{pp}$</td>
<td>5</td>
<td>0</td>
<td>3&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>Turbine</td>
<td>$\eta_{\text{is, Turb}}$</td>
<td>0.87&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1</td>
<td>0.95&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Pump</td>
<td>$\eta_{\text{is, Pump}}$</td>
<td>0.85&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1</td>
<td>0.95&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>Expansion valve</td>
<td>Isenthalpic&lt;sup&gt;c&lt;/sup&gt;</td>
<td>$\eta_{\text{is, EXV}} = 1&lt;sup&gt;c&lt;/sup&gt;$</td>
<td>Isenthalpic&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Generator</td>
<td>$\eta_{\text{Gene}}$</td>
<td>0.96&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1</td>
<td>0.98&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Ref. [26], <sup>b</sup>Ref. [39], <sup>c</sup>Ref. [40], <sup>d</sup>Ref. [41], <sup>e</sup>Ref. [42], <sup>f</sup>Ref. [21], <sup>g</sup>Ref. [43], <sup>h</sup>Ref. [44]
<table>
<thead>
<tr>
<th>Component</th>
<th>Energy balance equations</th>
<th>Entropy balance equations</th>
</tr>
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<tbody>
<tr>
<td>Turbine</td>
<td>$\dot{W}<em>{\text{Turb}} = \dot{m}</em>{ra}(h_1 - h_2)$</td>
<td>$\dot{S}<em>{\text{gen,Turb}} = \dot{m}</em>{ra}(s_2 - s_1)$</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{Turb}} = (h_1 - h_2) / (h_1 - h_{\text{is,2}})$</td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td>$\dot{W}_{\text{pump}} = \dot{m}(h_6 - h_4)$</td>
<td>$\dot{S}_{\text{gen,Pump}} = \dot{m}(s_6 - s_4)$</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{Pump}} = (h_{\text{is,6}} - h_5) / (h_6 - h_5)$</td>
<td></td>
</tr>
<tr>
<td>LTR</td>
<td>$h_7 - h_6 = h_3 - h_4$</td>
<td>$\dot{S}_{\text{gen,LTR}} = \dot{m}(s_4 + s_7 - s_3 - s_6)$</td>
</tr>
<tr>
<td>HTR</td>
<td>$\dot{m}(h_8 - h_7) = \dot{m}<em>{\text{pa}}(h</em>{10} - h_{11})$</td>
<td>$\dot{S}<em>{\text{gen,HTR}} = \dot{m}(s_8 - s_7) + \dot{m}</em>{\text{pa}}(s_{11} - s_{10})$</td>
</tr>
<tr>
<td>Evaporator</td>
<td>$\dot{m}(h_9 - h_8) = \dot{m}<em>{\text{gf}}(h</em>{13} - h_{14})$</td>
<td>$\dot{S}<em>{\text{gen,Evap}} = \dot{m}(s_9 - s_8) + \dot{m}</em>{\text{gf}}(s_{14} - s_{13})$</td>
</tr>
<tr>
<td>Condenser</td>
<td>$\dot{m}<em>{\text{ra}}(h_6 - h</em>{15}) = \dot{m}(h_4 - h_5)$</td>
<td>$\dot{S}<em>{\text{gen,Cond}} = \dot{m}(s_5 - s_4) + \dot{m}</em>{\text{cw}}(s_{16} - s_{15})$</td>
</tr>
<tr>
<td>Separator</td>
<td>$\dot{m}<em>h = \dot{m}</em>{\text{ra}} h_1 + \dot{m}<em>{\text{pa}} h</em>{10}$</td>
<td>$\dot{S}<em>{\text{gen,Sep}} = \dot{m}</em>{\text{pa}} s_{10} + \dot{m}_{\text{ra}} s_1 - \dot{m}s_9$</td>
</tr>
<tr>
<td></td>
<td>$\dot{m}<em>x = \dot{m}</em>{\text{ra}} x_{\text{ra}} + \dot{m}<em>{\text{pa}} x</em>{\text{pa}}$</td>
<td></td>
</tr>
<tr>
<td>Mixer</td>
<td>$\dot{m}<em>{ra} h_2 + \dot{m}</em>{\text{pa}} h_{12} = \dot{m} h_3$</td>
<td>$\dot{S}<em>{\text{gen,Mix}} = \dot{m}s_3 - \dot{m}</em>{\text{ra}} s_2 - \dot{m}<em>{\text{pa}} s</em>{12}$</td>
</tr>
<tr>
<td>expansion valve</td>
<td>$h_{11} = h_{12}$</td>
<td>$\dot{S}<em>{\text{gen,EXV}} = \dot{m}(s</em>{12} - s_{11})$</td>
</tr>
</tbody>
</table>

Table 4. Thermodynamic equations for the KSC-34 components.
Table 5. Details of the model validation using the data reported by Fallah [21].

<table>
<thead>
<tr>
<th>Stream</th>
<th>Enthalpy (kJ/kg)</th>
<th>Mass flow rate (kg/s)</th>
<th>Ammonia concentration (kg NH₃/kg solution)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ref.</td>
<td>Pres. value</td>
<td>Error (%)</td>
</tr>
<tr>
<td>1</td>
<td>1411</td>
<td>1411</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1326</td>
<td>1326</td>
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<tr>
<td>3</td>
<td>847.4</td>
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<tr>
<td>4</td>
<td>797.4</td>
<td>797.4</td>
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</tr>
<tr>
<td>5</td>
<td>59.7</td>
<td>59.7</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>62.46</td>
<td>62.44</td>
<td>0.03</td>
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<tr>
<td>7</td>
<td>112.4</td>
<td>112.3</td>
<td>0.09</td>
</tr>
<tr>
<td>8</td>
<td>169.2</td>
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<td>9</td>
<td>957.8</td>
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<td>10</td>
<td>187</td>
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<tr>
<td>11</td>
<td>33.51</td>
<td>33.47</td>
<td>0.12</td>
</tr>
<tr>
<td>12</td>
<td>33.51</td>
<td>33.47</td>
<td>0.12</td>
</tr>
</tbody>
</table>

**Net output power (kW)**

<table>
<thead>
<tr>
<th></th>
<th>Ref.</th>
<th>Present study</th>
<th>Error (%)</th>
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<tbody>
<tr>
<td>1672</td>
<td>1672</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

* $T_p=90 \, ^\circ\text{C}$, $P_p=25$ bar, $x_p=0.84$, Geofluid mass flow rate=200 kg/s, Geofluid input temperature =100 °C
Table 6. Thermodynamic parameters of KCS-34 in real, ideal, and unavoidable conditions.

<table>
<thead>
<tr>
<th>State</th>
<th>Fluid</th>
<th>Real</th>
<th>Ideal</th>
<th>Unavoidable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$h$ (kJ/kg)</td>
<td>$\dot{m}$ (kg/s)</td>
<td>$\dot{\psi}$ (kW)</td>
</tr>
<tr>
<td>1</td>
<td>$NH_3H_2O$</td>
<td>1481</td>
<td>11.32</td>
<td>222934</td>
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<tr>
<td>2</td>
<td>$NH_3H_2O$</td>
<td>1276</td>
<td>11.32</td>
<td>220310</td>
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<tr>
<td>3</td>
<td>$NH_2H_2O$</td>
<td>841.2</td>
<td>16.89</td>
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<td>4</td>
<td>$NH_2H_2O$</td>
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<td>16.89</td>
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<tr>
<td>5</td>
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<tr>
<td>6</td>
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<tr>
<td>7</td>
<td>$NH_2H_2O$</td>
<td>57.59</td>
<td>16.89</td>
<td>275860</td>
</tr>
<tr>
<td>8</td>
<td>$NH_3H_2O$</td>
<td>169.5</td>
<td>16.89</td>
<td>276136</td>
</tr>
<tr>
<td>9</td>
<td>$NH_2H_2O$</td>
<td>1091</td>
<td>16.89</td>
<td>279868</td>
</tr>
<tr>
<td>10</td>
<td>$NH_2H_2O$</td>
<td>300</td>
<td>5.572</td>
<td>56934.5</td>
</tr>
<tr>
<td>11</td>
<td>$NH_3H_2O$</td>
<td>-39.38</td>
<td>5.572</td>
<td>-107.8</td>
</tr>
<tr>
<td>12</td>
<td>$NH_3H_2O$</td>
<td>-39.38</td>
<td>5.572</td>
<td>-111.6</td>
</tr>
<tr>
<td>13</td>
<td>$H_2O$</td>
<td>512.3</td>
<td>89</td>
<td>7514</td>
</tr>
<tr>
<td>14</td>
<td>$H_2O$</td>
<td>337.3</td>
<td>89</td>
<td>3437</td>
</tr>
<tr>
<td>16</td>
<td>$H_2O$</td>
<td>75.58</td>
<td>244.7</td>
<td>402.8</td>
</tr>
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</table>

Table 7. The results of energy analysis.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Real</th>
<th>Ideal</th>
<th>Unavoidable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{W}_{Turb}$ (kW)</td>
<td>2317</td>
<td>2172</td>
<td>2214</td>
</tr>
<tr>
<td>$\dot{W}_{Pump}$ (kW)</td>
<td>85.2</td>
<td>45.87</td>
<td>52.58</td>
</tr>
<tr>
<td>$\dot{W}_{net}$ (kW)</td>
<td>2139</td>
<td>2139</td>
<td>2139</td>
</tr>
<tr>
<td>$\eta_{energy}$ (%)</td>
<td>0.1269</td>
<td>0.2075</td>
<td>0.1899</td>
</tr>
<tr>
<td>$\eta_{exergy}$ (%)</td>
<td>0.4849</td>
<td>0.8058</td>
<td>0.7289</td>
</tr>
</tbody>
</table>
Table 8. CEAM results on KCS-34 under real conditions.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{E}_{F,k}$ (kW)</th>
<th>$\dot{E}_{P,k}$ (kW)</th>
<th>$\dot{E}_{d,k}$ (kW)</th>
<th>$\mathcal{E}_k$ (%)</th>
<th>$\gamma_k = \dot{E}<em>{d,k} / \dot{E}</em>{F,k}$ (%)</th>
<th>$\gamma_k^* = \dot{E}<em>{d,k} / \dot{E}</em>{d, tot}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>2624</td>
<td>2317</td>
<td>307</td>
<td>88.3</td>
<td>11.7</td>
<td>19.96</td>
</tr>
<tr>
<td>LTR</td>
<td>453.5</td>
<td>167</td>
<td>286.5</td>
<td>36.8</td>
<td>63.18</td>
<td>18.63</td>
</tr>
<tr>
<td>Condenser</td>
<td>740.8</td>
<td>395.7</td>
<td>345</td>
<td>53.4</td>
<td>46.58</td>
<td>22.43</td>
</tr>
<tr>
<td>Pump</td>
<td>85.2</td>
<td>72.67</td>
<td>12.53</td>
<td>85.3</td>
<td>14.71</td>
<td>0.815</td>
</tr>
<tr>
<td>HTR</td>
<td>410.7</td>
<td>276</td>
<td>134.7</td>
<td>67.2</td>
<td>32.79</td>
<td>8.755</td>
</tr>
<tr>
<td>Evaporator</td>
<td>4076</td>
<td>3731</td>
<td>344.6</td>
<td>91.54</td>
<td>8.455</td>
<td>22.41</td>
</tr>
<tr>
<td>Expansion valve</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>100</td>
<td>0</td>
<td>0.975</td>
</tr>
<tr>
<td>Generator</td>
<td>2317</td>
<td>2224</td>
<td>92.69</td>
<td>95.99</td>
<td>4</td>
<td>6.026</td>
</tr>
<tr>
<td>Overall system</td>
<td>4076</td>
<td>2139</td>
<td>1538.02</td>
<td>52.48</td>
<td>37.73</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 9. CEAM results on KCS-34 under ideal conditions.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{E}_{F,k}$ (kW)</th>
<th>$\dot{E}_{P,k}$ (kW)</th>
<th>$\dot{E}_{d,k}$ (kW)</th>
<th>$\mathcal{E}_k$ (%)</th>
<th>$\gamma_k = \dot{E}<em>{d,k} / \dot{E}</em>{F,k}$ (%)</th>
<th>$\gamma_k^* = \dot{E}<em>{d,k} / \dot{E}</em>{d, tot}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>2172</td>
<td>2172</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LTR</td>
<td>89.98</td>
<td>55.66</td>
<td>34.32</td>
<td>61.86</td>
<td>38.14</td>
<td>13.04</td>
</tr>
<tr>
<td>Condenser</td>
<td>242.5</td>
<td>242.4</td>
<td>0.1505</td>
<td>99.94</td>
<td>0.062</td>
<td>0.572</td>
</tr>
<tr>
<td>Pump</td>
<td>45.87</td>
<td>45.87</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HTR</td>
<td>303.3</td>
<td>187.9</td>
<td>115.4</td>
<td>61.96</td>
<td>38.04</td>
<td>43.83</td>
</tr>
<tr>
<td>Evaporator</td>
<td>2654</td>
<td>2541</td>
<td>113.5</td>
<td>95.72</td>
<td>4.276</td>
<td>43.13</td>
</tr>
<tr>
<td>Expansion valve</td>
<td>12.72</td>
<td>12.72</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Generator</td>
<td>2172</td>
<td>2172</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Overall system</td>
<td>2654</td>
<td>2139</td>
<td>263.2</td>
<td>80.58</td>
<td>9.916</td>
<td>100</td>
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</table>

Table 10. CEAM results on KCS-34 under unavoidable conditions.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{E}_{F,k}$ (kW)</th>
<th>$\dot{E}_{P,k}$ (kW)</th>
<th>$\dot{E}_{d,k}$ (kW)</th>
<th>$\mathcal{E}_k$ (%)</th>
<th>$\gamma_k = \dot{E}<em>{d,k} / \dot{E}</em>{F,k}$ (%)</th>
<th>$\gamma_k^* = \dot{E}<em>{d,k} / \dot{E}</em>{d, tot}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>2322</td>
<td>2214</td>
<td>108.2</td>
<td>95.34</td>
<td>4.658</td>
<td>20.82</td>
</tr>
<tr>
<td>LTR</td>
<td>127.5</td>
<td>73.89</td>
<td>53.62</td>
<td>57.95</td>
<td>42.05</td>
<td>10.32</td>
</tr>
<tr>
<td>Condenser</td>
<td>302.5</td>
<td>270.2</td>
<td>32.25</td>
<td>89.34</td>
<td>10.66</td>
<td>6.208</td>
</tr>
<tr>
<td>Pump</td>
<td>52.58</td>
<td>49.98</td>
<td>2.601</td>
<td>95.05</td>
<td>4.948</td>
<td>0.5007</td>
</tr>
<tr>
<td>HTR</td>
<td>317.1</td>
<td>200.9</td>
<td>116.2</td>
<td>63.35</td>
<td>36.65</td>
<td>22.37</td>
</tr>
<tr>
<td>Evaporator</td>
<td>2935</td>
<td>2762</td>
<td>172.8</td>
<td>94.11</td>
<td>5.888</td>
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<tr>
<td>Expansion valve</td>
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<td>11.72</td>
<td>0</td>
<td>100</td>
<td>0.0001</td>
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<tr>
<td>Generator</td>
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<td>2192</td>
<td>22.14</td>
<td>99</td>
<td>1</td>
<td>4.261</td>
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<tr>
<td>Overall system</td>
<td>2935</td>
<td>2139</td>
<td>519.5</td>
<td>72.89</td>
<td>17.7</td>
<td>100</td>
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</tbody>
</table>
Table 11. Results of AEAM.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{E}_{d,k}$ (kW)</th>
<th>$\dot{E}^{\text{EN}}_{d,k}$ (kW)</th>
<th>$\dot{E}^{\text{EX}}_{d,k}$ (kW)</th>
<th>$\dot{E}^{\text{AV}}_{d,k}$ (kW)</th>
<th>$\dot{E}^{\text{UN}}_{d,k}$ (kW)</th>
<th>$\dot{E}^{\text{EN,AV}}_{d,k}$ (kW)</th>
<th>$\dot{E}^{\text{EN,UN}}_{d,k}$ (kW)</th>
<th>$\dot{E}^{\text{EX,AV}}_{d,k}$ (kW)</th>
<th>$\dot{E}^{\text{EX,UN}}_{d,k}$ (kW)</th>
<th>$IP_k$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>307</td>
<td>302.6</td>
<td>4.4</td>
<td>198.8</td>
<td>108.2</td>
<td>195.5</td>
<td>107.1</td>
<td>3.3</td>
<td>1.1</td>
<td>64.76</td>
</tr>
<tr>
<td>LTR</td>
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<td>170.8</td>
<td>115.7</td>
<td>232.88</td>
<td>53.62</td>
<td>126.19</td>
<td>44.61</td>
<td>106.69</td>
<td>9.01</td>
<td>81.28</td>
</tr>
<tr>
<td>Condenser</td>
<td>345</td>
<td>225.1</td>
<td>119.9</td>
<td>312.75</td>
<td>32.25</td>
<td>202.96</td>
<td>22.14</td>
<td>109.79</td>
<td>10.11</td>
<td>90.65</td>
</tr>
<tr>
<td>HTR</td>
<td>134.7</td>
<td>114.2</td>
<td>20.5</td>
<td>18.5</td>
<td>116.2</td>
<td>-0.1</td>
<td>114.3</td>
<td>18.6</td>
<td>1.9</td>
<td>13.73</td>
</tr>
<tr>
<td>Evaporator</td>
<td>344.6</td>
<td>240.1</td>
<td>104.5</td>
<td>171.8</td>
<td>172.8</td>
<td>80.4</td>
<td>159.7</td>
<td>91.4</td>
<td>13.1</td>
<td>49.85</td>
</tr>
<tr>
<td>Expansion valve</td>
<td>15</td>
<td>11.69</td>
<td>3.31</td>
<td>3.28</td>
<td>11.72</td>
<td>0</td>
<td>11.69</td>
<td>3.28</td>
<td>0.03</td>
<td>21.87</td>
</tr>
<tr>
<td>Generator</td>
<td>92.69</td>
<td>90.56</td>
<td>2.13</td>
<td>70.55</td>
<td>22.14</td>
<td>68.62</td>
<td>21.94</td>
<td>1.93</td>
<td>0.2</td>
<td>76.11</td>
</tr>
<tr>
<td>Overall system</td>
<td>1538.02</td>
<td>1163.10</td>
<td>374.92</td>
<td>1018.49</td>
<td>519.53</td>
<td>679.23</td>
<td>483.88</td>
<td>339.26</td>
<td>35.655</td>
<td>66.22</td>
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</table>

Table 12. Results of extended thermodynamic analysis.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{W}_{\text{net,ref}}$ (kW)</th>
<th>$\dot{S}_{\text{gen,tot,ref}}$ (kW/K)</th>
<th>$\dot{E}_{\text{w,ref}}$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>2344</td>
<td>7.828</td>
<td>2503</td>
</tr>
<tr>
<td>LTR</td>
<td>2276</td>
<td>8.014</td>
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</tr>
<tr>
<td>Condenser</td>
<td>2428</td>
<td>7.594</td>
<td>2412</td>
</tr>
<tr>
<td>Pump</td>
<td>2148</td>
<td>8.506</td>
<td>2698</td>
</tr>
<tr>
<td>HTR</td>
<td>2117</td>
<td>8.563</td>
<td>2736</td>
</tr>
<tr>
<td>Evaporator</td>
<td>2241</td>
<td>8.213</td>
<td>2604</td>
</tr>
<tr>
<td>Expansion valve</td>
<td>2139</td>
<td>8.538</td>
<td>2706</td>
</tr>
<tr>
<td>Generator</td>
<td>2209</td>
<td>8.286</td>
<td>2637</td>
</tr>
</tbody>
</table>

$\dot{W}_{\text{net,real}}=2139$ (kW), $\dot{S}_{\text{gen,tot,real}}=8.538$ (kW/K), $\dot{E}_{\text{w,real}}=2706$ (kW)
Fig. 1. Schematic diagram of the KCS-34.
Fig. 2. Comparison of the exergy destruction of a) endogenous and exogenous, b) avoidable and unavoidable, and c) conventional of obtained in present study and those reported in Ref. [21].
\[ \hat{E}_{d,k} = \hat{E}_{P,k} - \hat{E}_{P,k} \]

Conventional exergy analysis

Advanced exergy analysis

- \( \hat{E}_{EN}^{EN,UN} \)
  - The kth component work in real conditions and the rest component work in ideal conditions.
  - (hybrid cycle for Kth component)

- \( \hat{E}_{EN}^{EN,UN} \)
  - The kth component work in unavoidable conditions and the rest component work in ideal conditions.
  - (Table 3)

- \( \hat{E}_{UN} \)
  - All of components work in unavoidable conditions.
  - (Table 3)

\[ \hat{E}_{EN,AV}^{EN} = \hat{E}_{d,k} - \hat{E}_{d,k} \]
\[ \hat{E}_{EX,AV}^{EX} = \hat{E}_{d,k} - \hat{E}_{d,k} \]
\[ \hat{E}_{AV}^{AV} = \hat{E}_{d,k} - \hat{E}_{d,k} \]

Fig. 3. Flowchart of calculating the exergy destructions for the kth component (conventional and advanced).
Fig. 4. Improvement percentage of net output power, total entropy generation and wasted exergy for different components under the reference conditions.

Fig. 5. Improvement priority of components in KCS-34.
Biographies

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Parisa Kazemiani-Najafabadi is a doctor of mechanical engineering at the Department of Mechanical Engineering, Hakim Sabzevari University. Her research filed is modeling energy systems, especially power and cooling systems. According to the research filed, she has published over 10 papers in top journals.

Ehsan Amiri Rad has been an Associate Professor at the Department of Mechanical Engineering, Hakim Sabzevari University since June 2013. His main teaching contribution to undergraduates in engineering thermodynamic and exergy for postgraduate students. He is currently involved in energy optimization for power and cooling systems and has already carried out several projects. He has published over 40 papers in the various journals.