# Exergy Analysis for Energy Systems

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## 1 Introduction

The first law of thermodynamics (energy analysis) gives the quantitative results. It won't explain how effectively the process has been carried out. It will not consider the dissipative effects which play an important role in identifying system's bottlenecks. For example, in a thermal power plant, the condenser heat loss (energy loss) is approximately 40% of heat supply. It is unavoidable loss and this amount is fixed with the available sink temperature. In energy point of view, the combustion chamber efficiency is more than 90–95%. As per the energy analysis, a designer has to give more attention at condenser and less attention at combustion chamber. But really it is not correct. The exergy evaluation gives the results as per the real qualitative dissipative decays. As per the possibility in the improvement, it identifies and suggests for the improvements.

Exergy is defined as the work that is available in a gas, fluid, or mass, as a result of its nonequilibrium condition relative to some reference condition. The sea level, atmospheric condition is the ultimate sink for all terrestrial energy systems. The exergy method is a relatively new analysis technique in which the basis of evaluation of thermodynamic losses follows from the second law rather than the first law of thermodynamics. Thus, it belongs to that category of analyses known as the second law analyses. Another name which has been used, mostly in the past, is availability analysis. The demand for energy is growing worldwide, and this has to be met with various options in an environmentally friendly manner. Energy systems are receiving a great deal of attention to meet part of the growing energy demand

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with reduced global warming. Exergy analysis plays a major role, due to the growing energy demand, and the energy systems will receive a great deal of attention in the coming years to generate power and process heat from various energy sources to meet part of the global energy demand with high energy conversion efficiencies. The exergy analysis also is receiving attention to analyze various energy systems to identify the sources of irreversibilities and also aids to improve the performance of the systems. The generalized methodology of exergy evaluation has been reported for energy systems.

The second law analysis or exergy analysis is receiving a great attention from the last decade due to the ability to analyze a power generation system on a component basis and also as a whole system. Unlike the first law of thermodynamics which talks about energy balance for components or for the whole system, the second law provides insight into the performance of the energy system components and the whole energy system with quality point of view by analyzing the irreversibilities in the components, losses in the components, and the performance of them with operating conditions. In the literature, research investigations are conducted to improve the performance of the power generation system through exergy analysis leading to better design of system components and the whole power generation unit. With developments of advanced blade materials, combustion chamber, and with increased gas turbine inlet temperatures, the exergy analysis is becoming very important to improve the performance and design of energy system components and systems. Bejan et al. (1997) stressed the effective optimization and design of an energy system with exergy analysis. Dincer and Rosen (2004) discussed the role of exergy analysis for thermal energy systems. Any improvement in the energy systems based on the second law will result in greenhouse gas emissions leading to reduced global warming. Nikulshin et al. (2006) developed an exergy flow diagram for air refrigerator and also prepared a matrix to link the components to flow. Thermoeconomic evaluation has more weightage due to addition of cost component. Rosen (2002) stressed the exergy-based utilization rather than the energy-based and explained his views to clarify better meaning of efficiency and loss. Pavelka et al. (2015) generalized the formulation within the framework of classical irreversible thermodynamics, to minimize entropy production. Valero et al. (2006a, b) formulated the applications of the thermoeconomic analysis with suitable examples. Table 1 shows the difference between energy approach and exergy approach for evaluation of energy system.

The objective of the current work is to highlight the usage and potential of exergy analysis applicable to thermal and energy systems. Suitable examples are considered and demonstrated with the help of exergy evaluation.

**Table 1** Comparison of energy and exergy

| Energy | Exergy |
|---|---|
| Dependent on properties of only a matter or energy flow, and independent of environment properties | Dependent on properties of both a matter or energy flow and the environment |
| Has values different from zero when in equilibrium with the environment (including being equal to $mc^2$ in accordance with Einstein's equation) | Equal to zero when in the dead state by virtue of being in complete equilibrium with the environment |
| Conserved for all processes, based on the first law of thermodynamics (FLT) | Conserved for reversible processes and not conserved for real processes (when it is partly or completely destroyed due to irreversibilities), based on the second law of thermodynamics (SLT) |
| Can be neither destroyed nor produced | Can be neither destroyed nor produced in a reversible process, but it always destroyed (consumed) in an irreversible process |
| Appears in many forms (e.g., kinetic energy, potential energy, work, heat) and is measured in that form | Appears in many forms (e.g., kinetic exergy, potential exergy, work, thermal exergy), and is measured on the basis of work or ability to produce work |
| A measure of quantify only | A measure of quantity and quality |

## 2 Methodology

Figure 1 shows the steps involved in exergy analysis of energy system. In the first step, a material flow diagram for the proposed idea is to be prepared. The working fluid properties are required to evaluate the heat balance and exergy balance formulae. After the properties, mass balance, energy balance, and exergy balance formulae can be derived and simplified. With reference to the material flow diagram, at each state, mass, pressure, temperature, enthalpy, entropy, and exergy values can be evaluated. The total exergy of system is divided into two parts, i.e., chemical exergy and physical exergy. The chemical exergy of a fuel is the maximum obtainable work by allowing the fuel to react with air from the environment to produce environmental components of carbon dioxide, water vapor, oxygen, and nitrogen. In exergy balance of compressors and turbines, the chemical exergy cancels and so leaves the physical exergy which is the main contributor. However, chemical contribution plays the main role in fuel gas combustor, reactor, gasifier, etc. The physical exergy is the maximum obtainable work determined above the reference state. Irreversibility at each component can be identified and compared for all the components with suitable diagram. Exergy efficiency and irreversibility plots can be prepared for analysis. The plots can be analyzed to identify the strong and weak areas. The system design can be refined based on the exergy results.
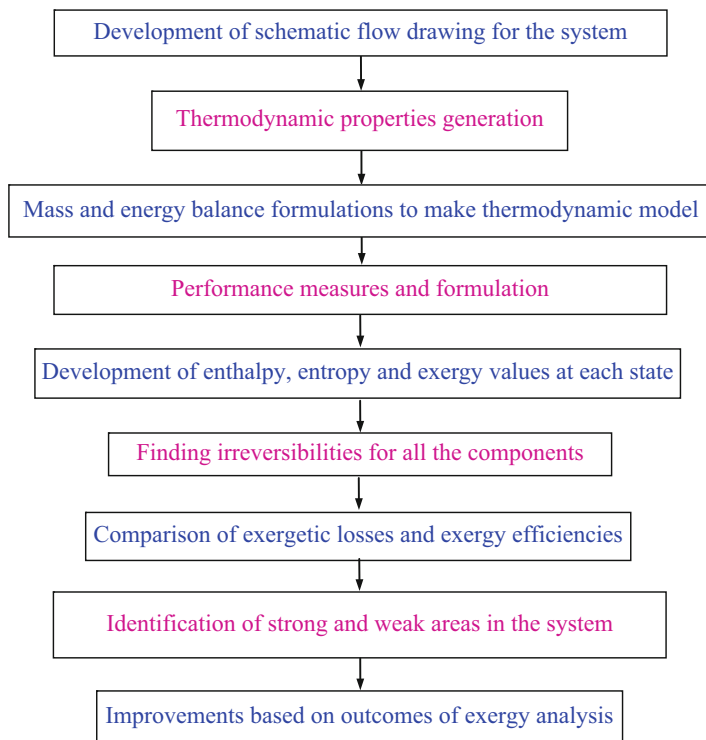
Development of schematic flow drawing for the system

Thermodynamic properties generation

Mass and energy balance formulations to make thermodynamic model

Performance measures and formulation

Development of enthalpy, entropy and exergy values at each state

Finding irreversibilities for all the components

Comparison of exergetic losses and exergy efficiencies

Identification of strong and weak areas in the system

Improvements based on outcomes of exergy analysis

**Fig. 1** Flowchart showing the methodology of exergy analysis

## 3 Results and Discussions

Figure 2 compares the exergetic loss in a typical combined cycle (CC) components
showed in percent of standard chemical exergy of fuel to study the role of deaerator
location in steam botting cycle (Srinivas 2009). The deaerator location influences
the bottoming cycle of exergetic losses especially on heat recovery steam generator
(HRSG) and exhaust losses. The deaerator placed in between the low pressure
(LP) and intermediate pressure (IP) heaters decreases the exergetic losses in both
the HRSG and exhaust. The exergetic losses at two mixing points, i.e., after IP and
LP superheaters, are comparatively low. These losses are added to the HRSG
exergetic loss. The major exergetic loss occurs in a gas turbine combustion chamber
(30%) and the minor in a deaerator. The deaerator location influences the heat
recovery and efficiency though its exergetic loss is minor. Finally, the location of
deaerator in between the LP and IP heaters reduces the total exergetic loss. In this
study, exergy diagonalization plays a crucial role in decision-making.

Similaly, Fig. 3 compares the exergetic losses in CC components with and
without the steam injection in the gas turbine combustion chamber (Srinivas
et al., 2008). The steam generated in bottoming steam plant can be drawn and
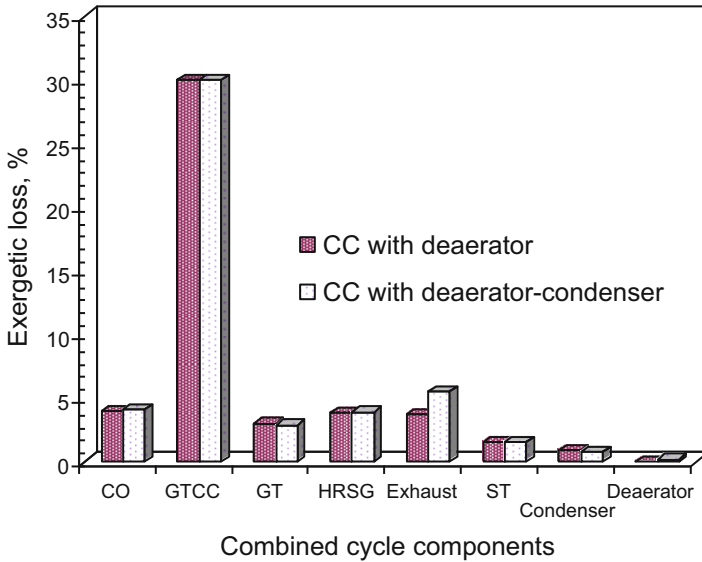
**Fig. 2** Comparison of exergetic losses in CC components in percent of standard chemical exergy input of fuel with two options of a deaerator arrangement

**Fig. 3** Comparison of the effect of steam injection on exergetic loss of the cycle components in percent of exergy input of fuel
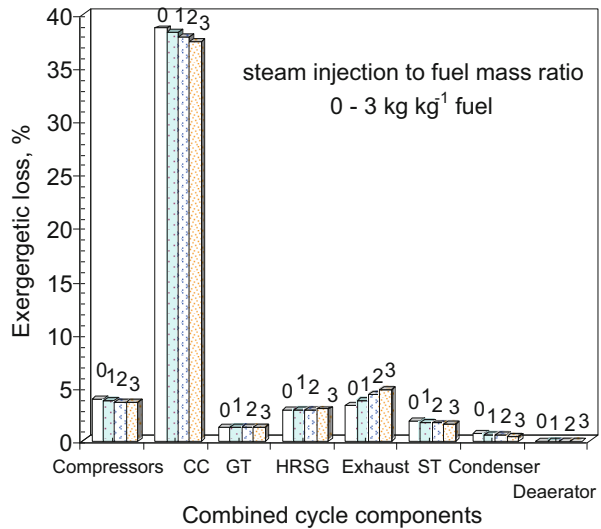


injected into gas turbine combustion chamber (GTCC) to result favarable performance and emission conditions.The steam injection is varied from 0 kg/kg fuel (without steam injection) to 3 kg/kg fuel. The exergetic losses in the compressors, combustion chamber (including gas reheater), steam turbines and condenser decreases with increase in steam injection and compared to the case without

steam injection. The exergetic losses in the remaining components i.e. gas turbine, HRSG, exhaust and deaerator increases with the steam injection. The exergetic loss in air compressor decreases with the steam injection due to the decreased airflow. The major part of the exergetic losses occurs in the gas turbine combustion chamber and gas reheater, which is 38.5% without steam injection. The steam injection in the combustion chamber decreases this exergetic loss to 37.4% with the steam injection of 3 kg/kg fuel. The exergetic loss in the chemical reaction is the difference of the availability between reactants and products. The steam injection in combustion increases the availability of both reactants and the products of the combustion but the increase in the products availability is more than the increase in the reactants. So the exergetic loss in combustion chamber decreases with the steam injection. The enthalpy and entropy change in gas turbine increases with steam injection, a minor increase in exergetic loss in gas turbine with steam injection. The loss of latent heat in the exhaust gas becomes high because a large amount of water vapor is included in the working fluid of the gas turbine. This leads to the increased exergetic loss in the exhaust gas with the steam injection. The quantity of steam for expansion in LP steam turbine and also in the condenser decreases with the steam injection. Therefore the exergetic losses in steam turbine and condenser decrease with the steam injection. The amount of bled steam into the deaerator increases with the steam injection and so the exergetic loss in the deaerator (minor loss) increases. On overall basis the total exergetic losses in combined cycle decreases with steam injection compared to the case without steam injection.

Figure 4 shows the consolidation result of total exergy loss with steam to fuel mass ratio. Approximately at 2 kg/kg of steam to fuel ratio, the total exergy loss becomes minimum. Therefore, based on exergy approach, the optimum steam to fuel mass ratio can be recommended. This study helps to find the breakeven for steam injection, i.e., the optimum level of steam injection to minimize the losses or maximize the efficiency.

Figure 5 compares exergetic losses in the components of the two Kalina cycle system (KCS) plants under consideration (Shankar Ganesh and Srinivas 2013). The plant with two possible options in heat exchanger arrangement has been studied. The maximum exergetic loss occurs in source (HRVG), and it is decreasing with the adoption of parallel arrangement. The major change can be seen in a high-temperature regenerator (HTRGN) due to its modified arrangement. Series to parallel change in heaters increases the exergetic losses in the components of turbine, condensate pump, low-temperature regenerator (LTRGN), and separator. But on overall basis, the parallel circuit results a reduced total exergetic losses for the plant. The exergy efficiency with series circuit is 62%; the same efficiency has been augmented to 65.2% with the parallel circuit.

Figure 6 compares the two cooling cogeneration cycles with the exergetic losses occurred in each component/processes of the cycles (Shankar and Srinivas 2014a, b). The exergy analysis is a system diagnosis used to highlight the strong and weak areas. So it helps in the improvement of the system by focusing more on the weakness. It also verifies the accuracy and identifies the mistakes in thermodynamic evaluation. The net entropy is always positive in a thermodynamic process or

**Fig. 4** Optimum steam to fuel mass ratio to minimize the exergetic loss
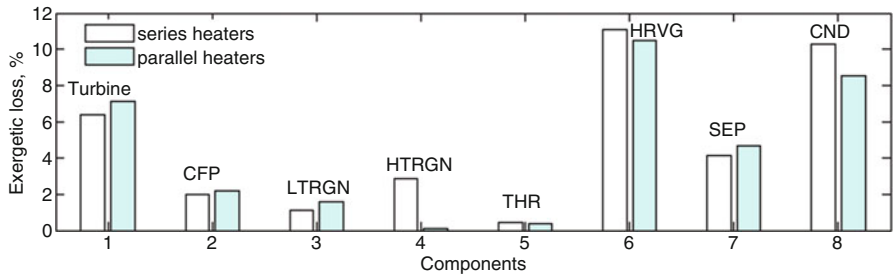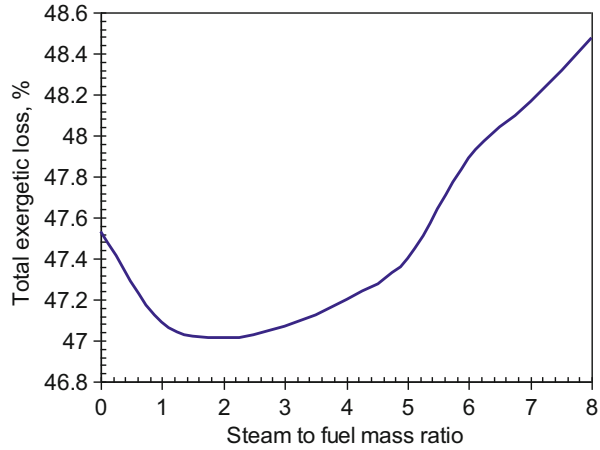




**Fig. 5** Comparison of Kalina cycle exergetic losses in series heaters and parallel heaters. *CFP* condensate feed pump, *CND* condenser, *HT* high temperature, *LT* low temperature, *RGN* regenerator, *SEP* separator, *THR* throttling

component. If it is negative, it shows a mistake in the formulation or solution of thermodynamic model. Figure 6 shows all positive values of exergetic losses, and it ensures the correctness of the thermodynamic model and its evaluation. Interestingly, the major exergetic loss in each cooling cogeneration cycle is different. In ammonia-water cycle, the major loss is in absorber, but the same for LiBr-water cycle is considerably low. Similarly the major exergetic loss in LiBr-water cycle is in HRVG and the same for ammonia-water cycle is low. These are different since the working fluid properties and the characteristics are different in the two cases. In ammonia-water cycle, the absorbent is water, whereas in LiBr-water cycle, the absorbent is LiBr salt. A considerable loss has been observed in the mixing process for both cycles at absorber inlet. It happened because of mixing of cold stream with the hot stream.
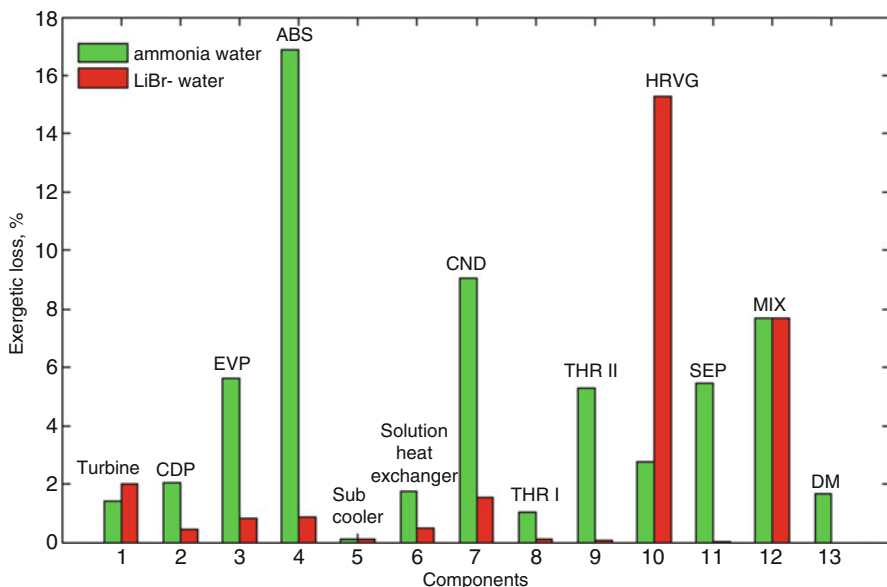
**Fig. 6** Comparison of exergetic losses in ammonia-water cooling cogeneration cycle and LiBr-water cooling cogeneration cycle

## 4   Conclusions

The advantages and potential of exergy analysis have been demonstrated by selecting suitable examples in energy systems. A methodology in the form of flowchart has been developed to understand the exergy analysis process. The exergy method helps in decision-making (place of deaerator location), preparing the optimum data (how much steam to be injected in GTCC), selection (selection of best configuration of plant), and choosing the working fluid (LiBr-water in place of aqua ammonia). Though energy does not give the complete information, exergy analysis is not possible without the energy evaluation.

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