Chapter 6

Application of Exergy Analysis to Energy Systems

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Additional information is available at the end of the chapter

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Abstract

Exergy analysis is a practical approach to evaluate the merit of energy conversion or distribution processes and systems. With the aid of an energy analysis, the performance of an energy conversion system cannot be evaluated efficiently and precisely. But, an exergy analysis complements and enhances an energy analysis. Exergy analysis involves the application of exergy concepts, balances, and efficiencies to evaluate and improve energy and other systems. Many scientists suggest that processes or sytems can be well evaluated and improved using exergy analysis in addition to or in place of energy analysis. Application of exergy analysis has given us more beneficial opportunities through a big part of a wide range of processes and systems particularly for the evaluation of energy systems and technologies as well as an environmental impact in all existing thermal and nuclear power plants. Conventional energy technologies, especially for power generation plants, have made numerous energy and exergy analyses and have produced beneficial results. Also, the use of energy and exergy analyses for advanced nuclear energy technologies can be expected to provide meaningful insights into performance that can assist in achieving optimal design concepts. Finally, explaining the analysis of thermal and nuclear power plant systems deals with exergetic approach.

Keywords: energy analysis, exergy analysis, energy conversion systems, power plant

1. Introduction

Thermodynamics permits the behavior, performance, and efficiency to be described for systems for the conversion of energy from one form to another. Conventional thermodynamic analysis is based primarily on the first law of thermodynamics, which states the principle of conservation of energy. An energy analysis of an energy conversion system is essentially an accounting of the energies entering and exiting. The exiting energy can be broken down into products and wastes. Efficiencies are often evaluated as ratios of energy quantities and are often used to assess and compare various systems. The thermodynamic losses that occur within a system often are not accurately identified and assessed with energy analysis.

Exergy is defined as the maximum amount of work that can be produced by a stream or system as it is brought into equilibrium with a reference environment, and it can be thought of as a measure of the usefulness or quality of energy. Exergy is consumed during real processes due to irreversibilities and conserved during ideal processes. The exergy analysis nomenclature used here follows that proposed by Kotas et al. [1].

Exergy analysis is a powerful tool for developing, evaluating, and improving an energy conversion system. The growing energy supply and demand have created an interest toward the plant equipment efficiency and the optimization of existing thermal power plants. At present, most of the power plants are going to be designed by the energetic performance criterion which is based on the first law of thermodynamics. Energy losses taking place in a system can be easily determined by using exergy analysis.

The exergy concept has gained considerable interest in the thermodynamic analysis of thermal processes and plant systems since it has been seen that the first law analysis has been insufficient from an energy performance standpoint. The system energy balance is not sufficient for the possible finding of the system imperfections.

There is a new technology for high-temperature air combustion and ultrahigh-temperature combined cycle. In this case, it is necessary to study the exergy analysis on combustion and thermodynamic processes, because ordinary energy analysis does not have any evaluation supported at its temperature level. In this particular field of engineering, it is difficult to use the ambient temperature energy of air and water, which are widely available. In a thermodynamic cycle, it is necessary to consider the power generation, which includes many kinds of effective and invalid items. The exergy analysis must be introduced to analyze power generation and heat pump cycles against energy analysis. Recently, a large number of studies based on exergy analysis have been carried out by many researchers all over the world in various system applications [2].

The benefits of exergy analysis are numerous compared to energy analysis. Some of the more significant ones follow below:

- Exergy efficiencies are always the measures of the approach to true ideality and provide more meaningful information when assessing the performance of energy systems. Also, exergy losses clearly identify the locations, causes, and sources of deviations from ideality in a system.
- Exergy methods can help evaluate the thermodynamic values of the product energy forms in complex systems with multiple products (e.g., cogeneration and trigeneration plants).
- Exergy-based methods can be used to improve economical and environmental assessments.
- Exergy can improve understanding of terms like energy conservation and energy crisis.
- Exergy methods can help in optimization activities.

There has been an increasing interest in using energy and exergy modeling techniques for energy utilization assessments in order to attain energy and financial savings [3].

All energy conversion systems have to be analyzed in terms of energetic, economic, and environmental aspects. Exergy-based analyses are very convenient methods for assessing the performance of energy conversion systems. Exergy is the maximum work that can be obtained from a system. Exergy-based analyses help determine the irreversibilities (entropy generation) and how a source can be used effectively. There are a few studies on advanced exergy-based analyses of power-generating systems in the open literature [4–13].

Rosen [4] presented energy-based and exergy-based comparisons of coal-fired and nuclear electrical-generating stations. Overall energy and exergy efficiencies, respectively, are 37 and 36% for the coal-fired process and 30 and 30% for the nuclear process. The losses in both plants exhibit many common characteristics. Naterer et al. [5] analyzed the coal-fired thermal power plant with measured boiler and türbine losses. Tsatsaronis and Moung-Ho [6] were the first to develop the concepts of avoidable and unavoidable exergy destruction, which were used to determine the potential of improving the thermodynamic performance and cost-effectiveness of a system. Morosuk and Tsatsaronis [7] applied advanced exergy analysis to a simple gas turbine cycle to assess its performance and discussed their calculation methods in detail. Khaliq and Kaushik [8] studied thermodynamic methodology for the performance evaluation of combustion gas turbine cogeneration system with reheat. The effects of process steam pressure and temperature used in the design of heat recovery steam generator, and reheat on energetic and exergetic efficiencies has been investigated. Koroneos et al. [9] discussed the exergy analysis of solar energy, wind power, and geothermal energy, and renewable energy sources are compared with the nonrenewable energy sources on the basis of efficiency. Ivar et al. [10] studied the exergy analysis of a natural-gas fired power plant with CO_2 capture. It indicates that maximum exergy is destroyed during the combustion and steam generation process, which represents over 80% of the total exergy destruction in the overall system. Petrakopoulou et al. [11] studied a combined power plant using advanced exergy and conventional analyses and demonstrated the superiority of the former. They reported that an advanced exergy analysis provided a wide range of optimization strategies and potential improvements. Taner [12] studied the energy and exergy analysis of a sugar factory model in Turkey and investigated within a general context to provide energy saving by reducing energy and exergy losses in the sugar production process. In another study, Taner [13] discussed the performance of a proton exchange membrane (PEM) fuel cell in terms of its pressure and voltage parameters and researched by experimental optimization to improve the performance, efficiency, and development of modeling and simulations of PEM fuel cells.

2. Comprehensive energy and exergy analyses

In general, open systems have mass, heat, and work interactions, and closed systems have heat and work interactions. The mass conservation equation can be written for an open system (control volume) as follows:

$$\sum_{i} m_i - \sum_{e} m_e = 0 \tag{1}$$

Energy, being subject to a conservation law (neglecting nuclear reactions), can be neither generated nor consumed. For a nonsteady flow process in a system during a finite time interval, energy balance can be written as follows [14]:

$$\text{Energy input} - \text{Energy output} = \text{Energy accumulation} \tag{2}$$

The first law energy balance equation for the control volume system is

$$\sum_{i} (h + ke + pe)_i m_i - \sum_{e} (h + ke + pe)_e m_e + \sum_{r} Q_r - W = 0 \tag{3}$$

where Q_r is the heat transfer into the system across r region on the system boundary; W is the work (including all forms of work) transferred out of the system; m_i and m_e *denote*, *respectively*, the rate of mass input and exits; and h, ke, and pe are the specific values of enthalpy, kinetic energy, and potential energy, respectively [14].

For a nonsteady flow process in a system, exergy balance can be written as follows [14]:

$$\text{Exergy input} - \text{Exergy output} - \text{Exergy consumption} = \text{Exergy accumulation} \tag{4}$$

Exergy is consumed due to irreversibilities. Exergy consumption is proportional to entropy creation. The main important difference between energy and exergy: energy is conserved, while exergy, a measure of energy quality or work potential, can be consumed.

The general exergy balance for the above system can also be expressed as [15]:

$$Ex_i - Ex_e = Ex_{heat} - Ex_{work} + Ex_{mass,\,i} - Ex_{mass,\,e} = Ex_{dest} = I \tag{5}$$

Assuming that flows are one-dimensional and the input and output terms in Eq. (5) are net quantities, the following may be written:

$$\sum_{i} m_i ex_i - \sum_{e} m_e ex_e + \sum_{r} Ex_{Qr} - Ex_W - I = 0 \tag{6}$$

The first two terms on the left-hand side of Eq. (6) represent the net input rate of exergy associated with matter, the third term the net input rate of exergy associated with heat, the fourth term the net output rate of exergy associated with work, and the fifth term the rate of irreversibility.

The thermal exergy transfer (Ex_{Qr}) at a constant temperature of T_r and the work exergy (Ex_W) may be calculated from the following equations:

$$Ex_{Qr} = Q_r\left(1 - \frac{T_r}{T_0}\right) \tag{7}$$

$$Ex_W = W \tag{8}$$

The rate of irreversibility, I, equals to exergy loss as

$$I = T_0 S_{gen} \tag{9}$$

This statement equals to the exergy destruction in the real process, where the subscript 0 indicates properties at the reference environment of P_0 and T_0. The specific exergy of a mass flow with negligible potential and kinetic energy changes may be written as

$$ex = \left[(h - h_0) - T_0(s - s_0)\right) + \left[\sum_j \left(\mu_{j0} - \mu_{j00}\right) x_j\right] \tag{10}$$

where x_j denotes the mass fraction of species j, s is the specific entropy, μ_{j0} is chemical potentials for each of the j components, and the subscript 0 refers to a quantity evaluated with respect to a reference environment. It is assumed to be reversible processes in which its temperature T_0, pressure P_0, and the chemical potentials, μ_{j00}, for each of the j components presented remain constant. The reference environment is in stable equilibrium [14].

The energy or the first law efficiency η of a system or system component is defined as the ratio of energy output to the energy input of system or system component, i.e.,

$$\eta = (\text{Desired output energy/Input energy supplied}) \tag{11}$$

The second law efficiency is defined as

$$\zeta = (\text{Desired output/Maximum possible output}) \tag{12}$$

Energy-related systems commonly have been designed and evaluated using the first law heat balances. But such calculations neglect the variation in the quality of the energy throughout a system. As a result, losses and inefficiencies are not evaluated realistically.

An exergy analysis should be conducted only after the validity of the mass, and energy balances has been confirmed. The thermodynamic analysis should be evaluated that an exergy balance is obtained by combining the corresponding energy and entropy balances [16].

A simple procedure for performing a comprehensive exergy analysis of such a system involves the following steps:

- Subdivision of the process under consideration into each system component (process or subprocess), depending on the depth of detail and understanding desired from the analysis.
- Calculation of the conventional mass and energy balances on the process and definition of all basic quantities (e.g., work and heat) and properties (e.g., temperature and pressure).
- Based on the nature of the process, the acceptable degree of analysis complexity and accuracy, and select a reference environment model.
- Calculation of the energy and exergy values, relate to the selected reference environment model.

- Calculation of the exergy balances including the determination of exergy consumptions.
- Select the efficiency definitions, depending on the measures of merit desired, and evaluate the efficiencies.
- Detailed evaluation of each system component based on the results, and draw appropriate conclusions and recommendations relating to such issues as design changes, retrofit plant modifications, etc.

3. Application of exergy analysis to energy systems

The types of applications of exergy methods to energy systems are extremely varied and include the following subgrouped as (a) utility, (b) industrial, (c) residential-commercial, and (d) transportation. Application of the exergy analysis may be applied predominantly among industrial energy systems.

The energy-utilization efficiency of a macrosystem, such as a region or country, can be assessed beneficially using exergy analysis. This section illustrates how the efficiency of energy utilization in a particular macrosystem, region, or country can be examined using both energy and exergy analyses.

The relation between energy resources and sectors of a macrosystem can be modeled as in **Figure 1**. The energy resources considered are coal, petroleum, natural gas, nuclear energy, and hydraulic energy. Renewable energy resources (e.g., solar energy, hydropower, biomass, geothermal, wind) can be neglected since the quantity is minor relative to other resources.

The utility sector includes processes for electricity generation using both conventional sources, such as fossil and nuclear power plants, and alternative sources, such as solar energy,

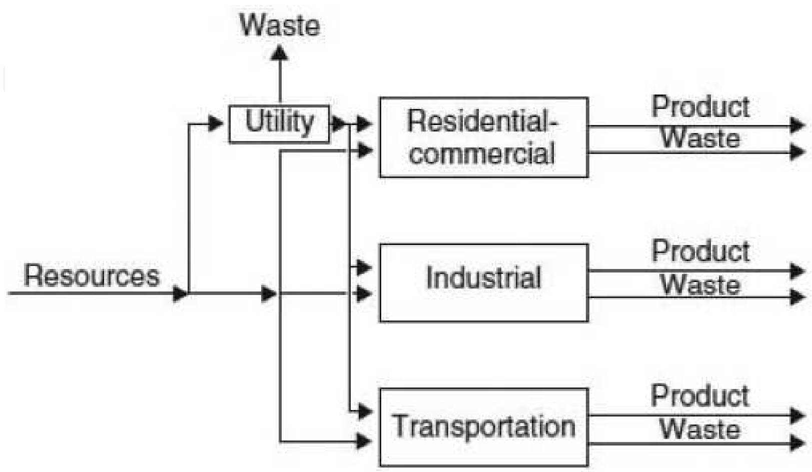

Figure 1. The diagram of the energy flows in a macrosystem.

hydropower, biomass, geothermal, wind, etc. It can be expected that performing an exergy analysis will be meaningful for performance comparisons, assessments, and improvement for all conventional and alternative power plants with a low efficiencies. Energy and exergy utilization efficiencies for utility sector, η and ζ, can be calculated from the given above equations, respectively.

Generally, the performance of thermal power plants is evaluated through energetic performance criteria based on the first law of thermodynamics, including electrical power and thermal efficiency. In recent decades, the exergetic performance based on the second law of thermodynamics has found a useful method in the design, evaluation, optimization, and improvement of thermal power plants. The exergetic performance analysis cannot only determines magnitudes, location, and causes of irreversibilities in the plants but also provides more meaningful assessment of plant individual component efficiency [17]. Lately, many researchers have concentrated their attention on exergy analysis of thermal power plants to optimize energy quality.

The industrial sector (petrochemical, chemical, and metallurgical processes, heating and cooling systems, etc.) is the most complex for determining overall efficiency and effectiveness values due to the profusion of different uses of energy. Exergy methods are used in many industries because they provide powerful tools for analyzing, assessing, designing, improving, and optimizing systems and processes [14].

In this sector, the energy consumption may be grouped as (1) mechanical drive, (2) process steam, (3) direct heat, (4) space heating, and (5) others, such as lighting, electrolytic processes, and miscellaneous applications. Relations used to calculate energy and exergy efficiencies of process steam, direct heat, and space heating are similar, expecting to the process steam, direct heat, and space heating temperatures [18].

Residential-commercial sector includes residential, commercial public, and agriculture activities (lighting, water heating, space heating, cooking, refrigerating, air conditioning, etc.), while it uses various energy carriers. Utilization of renewable energy may be spread, such as from sunlight to heat water, from geothermal to heat water and space, and from biowaste for general use.

The only specific application for which energy and exergy consumptions have been estimated in the transportation sector is transportation of fuel, because the use of energy sources as raw material is considered to be non-energy use.

Figure 2 shows the distribution of the world electricity use by sector over the period of 2015–2040. Electricity use increases the most in industrial, residential, and commercial buildings over the period of 2015–2040 [19].

Net electricity generation in the world increases an average 1.0%/year from 2015 to 2040, so it is very important to carry out an energy analysis of power generation plants with low efficiency.

One of the areas is environmental impact in which applications of exergy are expanding. The effect of energy resource utilization on the environment should be addressed by way of using exergy. Although the exergy of an energy form or a substance is a measure of its

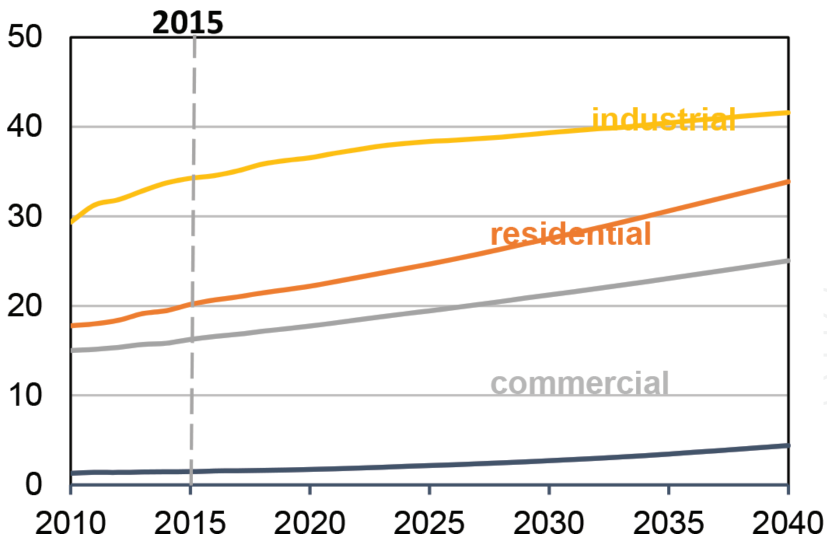

Figure 2. World electricity use by sector (quadrillion Btu).

usefulness, exergy is also a measure of its potential to cause change. Another area in which applications of exergy are increasing is that of economics. In the analysis and design of energy systems, techniques are often used that combine especially thermodynamics with economics to achieve optimal designs.

Currently, 80% of electricity in the world is approximately produced from fossil fuels (coal, petroleum, fuel oil, natural gas) and fired thermal power plants, while 20% of the electricity generation from renewable energy sources such as hydraulic, nuclear, wind, solar, geothermal, and biogas [20]. In recent decades, the exergetic performance analysis is found as a useful method in the design, evaluation, optimization, and improvement of nuclear and thermal power plants. The energetic and exergetic performance analyses are carried out for the existing coal-fired and nuclear power plants to identify and enhance the performance criteria.

3.1. Energy and exergy analyses of nuclear power plant

A detailed flow diagram for a nuclear power plant is shown in **Figure 3**. The diagram is divided into four main sections:

i. Steam generation: Heat is produced and used to generate and reheat steam. In the nuclear power plant, four natural circulation steam generators each produce steam.

ii. Power production: The steam produced in the steam generation section is passed through turbine generators that are attached to a transformer. Extraction steam from several points on the turbines preheats feedwater in several low-pressure and high-pressure heat exchangers and one deaerator.

iii. Condensation: Cooling water from the lake or sea condenses the steam exhausted from the turbines. The flow rate of cooling water is adjusted so that a specified temperature increase in the cooling water is achieved across the condenser.

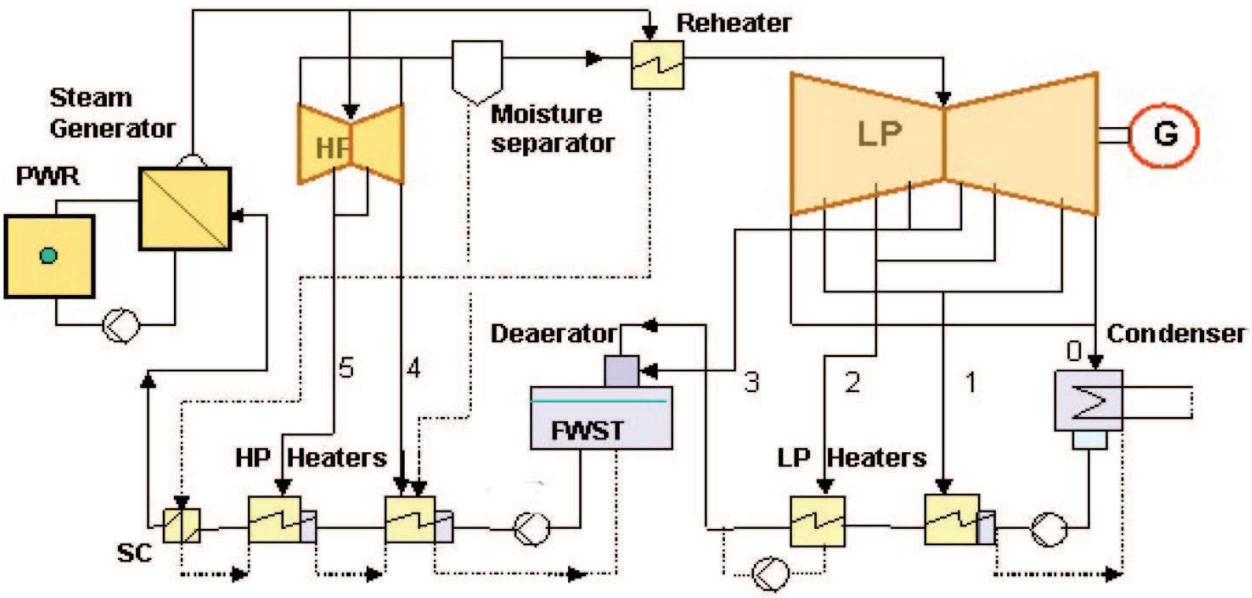

Figure 3. The simplified flow diagram of nuclear power plant.

iv. Preheating: The temperature and pressure of the feedwater are increased in a series of pumps and feedwater-heater heat exchangers.

A continuous mass flow diagram for one unit of the power plant modeled in this study includes the main components such as high- and low-pressure turbines, a reactor, pumps, a dearetor, a steam generator, a condenser, low- and high-pressure feed water heaters (**Figure 3**). The thermodynamic models are based on fundamental mass and energy balances. Using the energy and mass balance equations for each component in the power plant model, it is possible to compute energy and exergy contents in terms of turbine power outputs, pump power consumptions, energy and exergy flows at each node of the plants, first and second component efficiencies, and component irreversibilities in the plants [21].

There are three types of energy transfer, namely, works, heat transfer, and energy associated with mass transfer in open system. The first law of thermodynamics or energy balance for the steady flow process is given:

$$\dot{Q} - W_{cv} = \sum_{e} \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g z_e \right) - \sum_{i} \dot{m}_i \left(h_i + \frac{\dot{V}_i^2}{2} + g z_i \right) \tag{13}$$

where Q is the heat transfer to system, W_{cv} the net work developed by the system, V is the bulk velocity of the working fluid, z is the altitude of the stream above the sea level, and g is the specific gravitational force.

Exergy flow equation for each part of the power plant is

$$\dot{E}x = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{14}$$

The second law can be expressed as

$$\dot{S}_g = \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i + \frac{\dot{Q}_s}{T_0} \tag{15}$$

where $\dot{S}_g$ represents the entropy generation rate for the process due to the irreversibilities. Two terms, namely, $\sum_i \dot{m}_i s_i$ and $\sum_e \dot{m}_e s_e$, are considered as the entropy transfer. $\dot{Q}_s = -\dot{Q}$ denotes the heat transfer rate for the instantaneous temperature T_0. The last term, $\dot{Q}_{sur}/T_0$, stands for the entropy transfer rate. The heat transfer above has been neglected as well as the kinetic, potential energies of the stream; one arrives at [21]

$$\dot{W}_{cv} = \dot{W}_u \cong \sum_i \dot{m}_i (h_i - T_0 s_i) - \sum_e \dot{m}_e (h_e - T_0 s_e) - T_0 \dot{S}_g \tag{16}$$

The reversible work can be obtained by adjusting the entropy generation term $\dot{S}_g = 0$:

$$\dot{W}_{rev} = \dot{W}_{u,\max} = \sum_i \dot{m}_i (h_i - T_0 s_i) - \sum_e \dot{m}_e (h_e - T_0 s_e) = \dot{m}[(h_i - h_e) - T_0 (s_i - s_e)] \tag{17}$$

The reversible work can be obtained as

$$\dot{\mathrm{W}}_{\mathrm{u,\max}} = \sum_{\mathrm{i}} \dot{\mathrm{m}}_{\mathrm{i}} \mathrm{ex}_{\mathrm{i}} - \sum_{\mathrm{e}} \dot{\mathrm{m}}_{\mathrm{e}} \mathrm{ex}_{\mathrm{e}} = \sum_{\mathrm{i}} \dot{\mathrm{E}}\mathrm{x}_{\mathrm{i}} - \sum_{\mathrm{e}} \dot{\mathrm{E}}\mathrm{x}_{\mathrm{e}} \tag{18}$$

The rate of irreversibility $\left(\dot{I}\right)$ equals to exergy loss as

$$\dot{I} = \dot{W}_{u,\max} - \dot{W}_u = T_0 \dot{S}_g \tag{19}$$

This statement equals to the exergy destruction in the real process. The equations of energy and exergy can be applied for the nuclear power plants in order to find out the irreversibility rates for the processes in the reactor.

Energy and exergy balance for the adiabatic turbine system can be written as

$$\dot{W}_t = \left(\dot{W}_u\right)_t = \sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e \tag{20}$$

The irreversibility rate as a measure of the exergy loss is

$$\dot{I}_t = \sum_i \dot{E}x_i - \sum_e \dot{E}x_e - \dot{W}_t = T_0 \left(\sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i \right) \tag{21}$$

The isentropic efficiency of turbine is

$$\eta_t = \frac{\left(\dot{W}_u\right)_t}{\left(W_{u,\max}\right)_t} = \frac{W_t^{\cdot}}{\left(\dot{W}_{u,\max}\right)_t} \tag{22}$$

and the exergy efficiency of turbine is

$$\zeta_t = \frac{\dot{W}_t + \sum_e \dot{E}x_e}{\sum_i \dot{E}x_i} \tag{23}$$

The internal power input for the pump can be given as

$$\dot{W}_p = \dot{m}_i h_i - \dot{m}_e h_e \tag{24}$$

The rate of irreversibility of pump is

$$\dot{I}_p = \sum_i \dot{E}x_i - \sum_e \dot{E}x_e - \dot{W}_p \tag{25}$$

The isentropic efficiency of pump is

$$\eta_{p=} \frac{\left(\dot{W}_{u,rev}\right)_p}{\left(W_u\right)_p} = \frac{\left(\dot{W}_{u,rev}\right)_p}{\dot{W}_p} \tag{26}$$

and the second law efficiency is

$$\zeta_t = \frac{\dot{W}_t + \sum_e \dot{E}x_e}{\sum_i \dot{E}x_i} \tag{27}$$

The reversible work for the heat transfer equals to the rate of irreversibilities in the heaters, coolers, reheaters, condensers, and steam generators. The expression is

$$\dot{I}_{HT} = \dot{W}_{rev} - \dot{W}_u = \dot{W}_{rev} = \sum_i \dot{E}x_i - \sum_e \dot{E}x_e \tag{28}$$

Because $\dot{\mathrm{W}}_{\mathrm{u}} = 0$, there is no useful work produced during the heat transfer. The second law efficiency can be defined as

$$\zeta_{HT} = \frac{\sum_e \dot{E}x_e}{\sum_i \dot{E}x_i} \tag{29}$$

3.2. Energy and exergy analyses of coal-fired power plant

Coal-based thermal power plant generally operates on Rankine cycle as shown in **Figure 4** [22]. Similarly, there are four main sections: steam generation, power production, condensation, and preheating.

The thermodynamic models are based on fundamental mass, energy, and exergy balance equations. The first law of thermodynamics or energy balance is

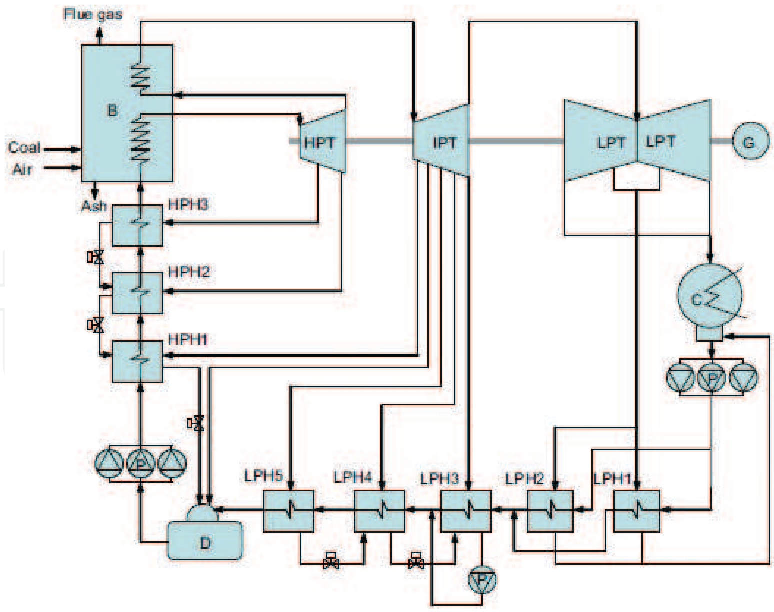

Figure 4. The simplified diagram of coal-fired thermal power plant.

$$\dot{Q} - W_{cv} = \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) - \sum_i \dot{m}_i \left(\frac{h_i + \dot{V}_i^2}{2 + gz_i} \right) \tag{30}$$

The energy of the first law efficiency of a system and/or system component is defined as the ratio of energy output to the energy input to system/component.

Entropy equation is analyzed with the following equation:

$$\dot{S}_g = \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i + \frac{\dot{Q}_s}{T_0} \tag{31}$$

where s_e, s_i, and S_g are the specific entropies at the inlet, outlet, and generation of the system, respectively. Balance equation for exergy is analyzed with following equation [22]:

$$\sum_\mathrm{i} \dot{\mathrm{m}}_\mathrm{i} \mathrm{ex}_\mathrm{i} - \sum_\mathrm{e} \dot{\mathrm{m}}_\mathrm{e} \mathrm{ex}_\mathrm{e} - \dot{\mathrm{E}}\mathrm{x}_\mathrm{Des} - \dot{\mathrm{E}}\mathrm{x}_{Heat} = \Delta \dot{\mathrm{E}}\mathrm{x}_{sys} \tag{32}$$

where ex_i and ex_e are the specific exergy at the inlet or outlet of the system components, respectively. Also, Ex_{Des} and Ex_{heat} are destructed exergy rate and exergy rate due to heat transfer, respectively.

$$\mathrm{ex} = \mathrm{ex}_{ph} - \mathrm{ex}_\mathrm{ch} \tag{33}$$

where ex_{ph} and ex_{ch} are the physical exergy and chemical exergy, respectively. The physical and chemical exergies can be defined as follows:

$$\mathrm{ex}_{ph} = (h_i - h_e) - T_0(s_i - s_e) \tag{34}$$

$$\mathrm{ex}_{ch} = \sum x_i ex^0_{ch} + RT \sum x_i \ln(x_i) \tag{35}$$

The energy and exergy efficiencies of all system can be defined as the ratio of total useful output to the system input. General definitions for energy and exergy efficiencies are

$$\eta_{en} = \frac{En^{\cdot}_{e}}{En^{\cdot}_{i}} \tag{36}$$

$$\eta_{ex} = \frac{Ex^{\cdot}_{e}}{Ex^{\cdot}_{i}} \tag{37}$$

where subscripts En and Ex stand for energy and exergy per unit time, respectively. For the whole thermal power plant, the exergy efficiency is

$$\eta_{Ex} = \frac{\dot{W}_{Nett}}{m_{coal}.ex_{coal}} \tag{38}$$

The other important exergetic performance criterion defined in this study is the amount of exergy loss rate per unit power output, and it can be written as the following equation:

$$\zeta = \frac{\dot{E}x_D}{\dot{W}_{Nett}} \tag{39}$$

4. Conclusion

A major contribution of exergy analysis to the evaluation of a system is provided through a thermoeconomic evaluation that considers not only the inefficiencies but also the costs associated with these inefficiencies and compares the latter with the investment expenditures to reduce inefficiencies. In general, the major driving force for all advances in thermal and nuclear power plants is thermal efficiency. Thermal efficiencies of modern power plants are varied from average 30% to 45%. Also, an exergy analysis identifies and evaluates the thermodynamic inefficiencies of these plants. The costs associated with these inefficiencies should be analyzed by comparing these costs with the investment expenditures needed to reduce thermodynamic inefficiencies.

In the analyses, the developed model for each power plant using the mass, energy and exergy balance equations, and system and component performance criteria such as thermal efficiency, exergy efficiency, and exergy destruction have been determined and compared with each other. Using the energy analyses of the energy loss in the condenser seems higher, but the largest exergy losses occur in the reactor pressure vessel with the highest exergy destruction in the nuclear power plant. According to the analysis, the main exergy loss of the nuclear power plant stem from the reactor pressure vessel [21]. Indeed, it is the worse component in the whole NPP due to the irreversibility of the energy transformation. This result means that the NPP has the greatest potential to improve the plant efficiency in new pressure vessel components. The percentage ratio of the exergy destruction to the total exergy destruction was found to be maximum in the reactor pressure vessel followed by the steam generator and then the turbine [21]. The first law analysis shows major energy loss that has been found to occur in condenser, while already its exergetic value is significantly low in coal-fired thermal plant. Also, the second law (exergy) analysis shows that the largest exergy losses occur in the combustion chamber or boiler [22].

Finally, there is a need for further work to develop a methodology for optimizing the power plant and to relate the overall efficiency to the rational efficiencies of its components or sub-systems to include in some significant new conceptual developments and beneficial interpretations. An exergy method of optimization gives logical solution improving the power production opportunities in thermal and nuclear power plants.

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