EXERGY ANALYSIS OF SIMPLE PROCESSES

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Contents

Summary

The real thermodynamic inefficiencies in an energy conversion system are related to exergy destruction and exergy loss. An exergy analysis identifies the system components with the highest exergy destruction and the processes that cause them. In this chapter, different types of system components such as chemical reactors, heat exchangers, and turbomachines are analyzed from the thermodynamic viewpoint. Furthermore, the irreversibilities associated with combustion, heat transfer, mixing, and pressure losses are considered separately to estimate the contribution of each form of irreversibility to the total exergy destruction in a steam generator. An exergy analysis of a simple cogeneration system is discussed in detail. For each system component, the exergy destruction, an exergy destruction ratio, and the exergetic efficiency are calculated. The evaluation of these variables provides useful information for improving the thermodynamic performance of the cogeneration system.

1. Thermodynamic Analysis of Single System Components

Energy conversion processes are governed by the laws of conservation of mass and energy. However, entropy is generated and exergy is destroyed by irreversibilities within a thermal system. Furthermore, exergy is lost, in general, when the exergy associated with a material or energy stream is rejected to the surroundings. In this section, different types of system components are analyzed from the thermodynamic viewpoint. The objectives are to calculate the real thermodynamic inefficiencies in each system component and to understand the effects that cause them. Sources of inefficiencies are related to exergy destruction and exergy loss. Either an exergy balance or an entropy balance together with the relationship $\dot{E}_D = T_0 \dot{S}_{\text{gen}}$ can be used to calculate the exergy destruction in a component. However, the exergy concept enables the definition of exergetic efficiencies, the calculation of exergy losses, and the calculation of costs (exergy costing) associated with each stream in the energy conversion system as well as the costs associated with the exergy destruction within a component (see *Thermoeconomic Analysis*).

The primary contributors to exergy destruction are irreversibilities associated with chemical reaction, heat transfer, mixing, and friction. The exergy destruction associated with heat transfer and friction is discussed in *Exergy Balance and Exergetic Efficiency*. Mixing of streams with differences in temperature, pressure, or chemical composition also causes exergy destruction.

When a material or energy stream is rejected to the surroundings (e.g., flue gas, cooling water and heat loss), the exergy associated with this stream is an exergy loss for the overall system. For streams of matter, the larger the flow rate and the higher the temperature of the stream, the larger the exergy loss. In addition, the larger the chemical exergy of the stream rejected to the surroundings (e.g., partial oxidation of a fossil fuel or unburned fuel), the higher the associated exergy loss. Examples include: exhaust gases in a stack, ash at the bottom of a steam generator or gasifier, cooling water in a condenser, vent stream in a deaerator, or blow down in a steam drum.

For component analysis, all material streams exiting a component are considered either as part of the product or as belonging to the definition of the fuel. Thus, the transfer of thermal exergy $\dot{E}_{q,\text{L}}$ to the surroundings is the only exergy loss in a component.

$$\dot{E}_{q,\text{L}} = \left(1 - \frac{T_0}{T_\text{b}}\right) |\dot{Q}_\text{L}|. \qquad (1)$$

The term $\dot{Q}_\text{L}$ denotes the heat transfer to the surroundings and T_b is the temperature on the boundary where the heat transfer occurs. The control volume enclosing the system component can be selected to encompass the system component and enough of its nearby surroundings so that the heat loss occurs at the ambient temperature T_0 and the term $\dot{E}_{q,\text{L}}$ in an exergy balance vanishes. Thus, the thermodynamic inefficiencies in a system component consist exclusively of exergy destruction ($\dot{E}_{\text{L},k} = 0$; see *Exergy Balance and Exergetic Efficiency*).

In the sign convention applied here, work done on the system and heat transferred to the system are positive. Accordingly, work done by the system and heat transferred from the system are negative. The exergy terms in the equations used here are all positive.

In the following sections, different types of plant components are analyzed from a thermodynamic viewpoint. For simplicity, only steady-state processes are considered.

1.1. Chemical Reactors

1.1.1. Combustion Chamber

During the combustion of a fossil fuel with an oxidant (air or oxygen), the chemical energy (exergy) of the fuel is converted mainly into internal energy of the combustion products ("heat release"). For given temperatures of the reactants, the chemical composition and the temperature of the gaseous reaction products depend on the fuel composition, the amount of oxidant supplied to the combustion chamber per mass unit of fuel, and the heat transfer to the surroundings ("heat loss"). Figure 1 shows the schematic diagram of a combustion chamber. More than the theoretically minimum amount of oxidant needs to be supplied to the combustion chamber in practice to achieve complete combustion of the fuel. Combustion processes are often accompanied by heat transfer, e.g. in the furnace of a steam generator (Section 2.1).

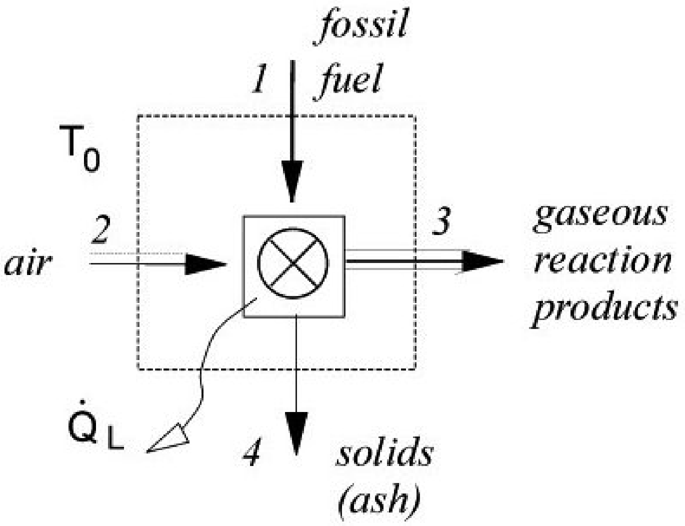

Figure 1: Combustion chamber.

The combustion process involves several chemical reactions by which the combustible chemical substances supplied with the fuel are oxidized and the temperature of inert chemical components is increased. The gaseous reaction products might contain unburned fuel and the products of incomplete combustion (e.g., carbon monoxide CO). The solids stream leaving the combustion chamber when a solid fuel is used contains unburned fuel. The mass balance for the combustion chamber yields:

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 + \dot{m}_4 . \qquad (2)$$

The steady-state form of the energy balance is

$$\dot{H}_1 + \dot{H}_2 = \dot{H}_3 + \dot{H}_4 - \dot{Q}_\mathrm{L}, \tag{3}$$

where $\dot{Q}_\mathrm{L}$ is the heat transfer to the surroundings (negative numerical value).

Combustion is intrinsically a very significant source of irreversibility. Such irreversibilities can only be identified by an entropy or an exergy balance. The entropy generation $\dot{S}_\mathrm{gen,cc}$ is given by

$$\dot{S}_\mathrm{gen,cc} = (\dot{S}_3 + \dot{S}_4) - (\dot{S}_1 + \dot{S}_2) - \frac{\dot{Q}_\mathrm{L}}{T_\mathrm{b}}. \tag{4}$$

The exergy destruction rate $\dot{E}_\mathrm{D,cc}$ due to irreversibilities in the combustion process is obtained from an exergy balance

$$\dot{E}_\mathrm{D,cc} = (\dot{E}_1 - \dot{E}_4) - (\dot{E}_3 - \dot{E}_2) \tag{5}$$

$$= \underbrace{\dot{m}_4(e_1 - e_4) + (\dot{m}_1 - \dot{m}_4)(e_1 - e_3)}_{\dot{E}_\mathrm{F,cc}} - \underbrace{\dot{m}_2(e_3 - e_2)}_{\dot{E}_\mathrm{P,cc}} \quad , \tag{6}$$

where $\dot{E}_\mathrm{F,cc}$ and $\dot{E}_\mathrm{P,cc}$ denote the fuel and the product of the combustion chamber expressed in exergy terms, respectively (see *Exergy Balance and Exergetic Efficiency*).

Chemical reaction is one of the most significant sources of exergy destruction. Fuel and oxidant spontaneously react according to relatively unconstrained combustion reactions. Preheating the reactants (fuel and oxidant) and reducing the oxidant-fuel ratio are two measures that increase the combustion temperature in an adiabatic combustion process and result in a higher thermodynamic efficiency. However, only slight improvements can be achieved by these measures.

The closer the occurrence of chemical reactions to the thermodynamic equilibrium,, the lower are the irreversibilities. In technical combustion processes, the combustion temperature is restricted by material limitations and the formation of nitrogen oxides at high temperatures.

Richter und Knoche presented theoretical considerations for reducing the irreversibilities in a combustion process by preventing immediate contact of fuel with oxygen and using intermediate chemical reactions. Metal oxides serve as oxygen carriers in these intermediate reactions. Similar considerations were applied to the HECAP (Hydrogen and Electric power generation using CArbonaceous materials and high temperature Process heat; see *Strengths and Limitations of Exergy Analysis*) concept in which sulfuric acid is the oxygen carrier.

Irreversibilities associated with heat transfer, mixing, and friction, also decrease the thermodynamic performance (exergetic efficiency) of a combustion process. Compared with the exergy destruction due to chemical reactions, mixing and friction effects are of minor importance.

1.1.2. Gasifier

Gasification is the conversion of the hydrocarbons contained in a solid fuel into a combustible gas. In addition to the fuel, air or oxygen, and steam are supplied to a gasifier (Figure 2). In the reactor, partial combustion, gasification, and other chemical reactions occur simultaneously at high temperatures and usually moderate pressures. The result is a product gas that is in most gasification processes rich in hydrogen H_2 and carbon monoxide CO. In addition, the product gas contains carbon dioxide CO_2, steam H_2O, and some methane CH_4. Gasification conditions favor the conversion of solid-fuel-bound nitrogen to gaseous nitrogen N_2 and ammonia NH_3. The sulfur contained in the solid fuel is converted to gaseous hydrogen sulfide H_2S and carbonyl sulfide COS. Finally, fine solid particles (ash, unreacted fuel) and small amounts of hydrogen cyanide HCN are also present in small amounts in the gaseous gasification products stream 4. This stream represents a synthetic fuel and is therefore called syngas or synfuel. The ash stream contains unreacted carbon and sulfur. From the exergetic viewpoint, the gasifier has two products: the chemical exergy of the syngas and the difference in physical exergy of all material streams between the outlet and inlet of the gasifier. The chemical exergy of the syngas represents the primary desired exergy form in a gasifier. The higher the gasifier operating temperature, the higher the percentage of physical exergy in the syngas. The carbon conversion ratio for a gasifier is defined as the percentage of carbon supplied by the fuel (stream 1) that is contained in the gas product stream 4.

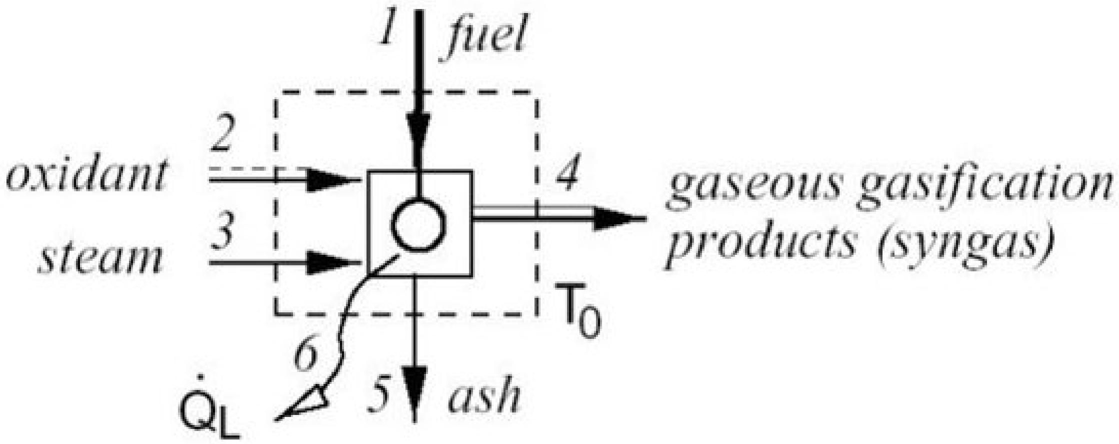

Figure 2: Gasifier.

At steady-state, the mass balance yields

$$\dot{m}_1 + \dot{m}_2 + \dot{m}_3 = \dot{m}_4 + \dot{m}_5 . \qquad (7)$$

The energy balance for the gasifier is

$$\dot{H}_1 + \dot{H}_2 + \dot{H}_3 = \dot{H}_4 + \dot{H}_5 - \dot{Q}_L \quad , \qquad (8)$$

whereas the entropy generation $\dot{S}_{\mathrm{gen,g}}$ is given by

$$\dot{S}_{\mathrm{gen,g}} = \dot{S}_4 + \dot{S}_5 - \frac{\dot{Q}_{\mathrm{L}}}{T_{\mathrm{b}}} - (\dot{S}_1 + \dot{S}_2 + \dot{S}_3) \quad . \tag{9}$$

The exergy destruction is calculated from an exergy balance

$$\dot{E}_{\mathrm{D,g}} = \underbrace{(\dot{E}_1 - \dot{E}_5)}_{\dot{E}_{\mathrm{F,g}}} - \underbrace{(\dot{E}_4 - \dot{E}_2 - \dot{E}_3)}_{\dot{E}_{\mathrm{P,g}}} \tag{10}$$

In general, the exergetic efficiency depends on the type of gasifier (e.g., entrained flow, fluidized-bed, or fixed-bed), the oxidant (air or oxygen), the chemical composition of the solid fuel, the moisture content of the fuel at the gasifier inlet, the supply of the solid fuel (water/slurry or dry), the operating parameters (gasification temperature and pressure), the amount of steam and additives (e.g., limestone) and the heat transfer to the surroundings.

The main sources of thermodynamic inefficiencies in a gasifier are the chemical reactions. Heating of inert chemical components, mixing of streams with differences in temperature, pressure, and chemical composition as well as pressure drop due to friction also contribute to the exergy destruction. With increasing gasification temperature, both the relative amount of combustion and the required internal heat transfer in the gasifier increase; thus, the exergy destruction within the gasifier increases. For a given carbon conversion ratio, the exergy destruction in an adiabatic gasifier can be reduced by preheating the reactants and by reducing the temperature of the syngas at the outlet.

The thermodynamic performance of a gasifier can be evaluated by a properly defined exergetic efficiency (see *Exergy Balance and Exergetic Efficiency*). However, a cold gas efficiency is often used in practice. The cold gas efficiency η_{cge} is defined as the heating value of the purified syngas divided by the heating value of the solid fuel fed into the gasifier:

$$\eta_{\mathrm{cge}} = \frac{\dot{m}_4 HHV_{\mathrm{syngas}}}{\dot{m}_1 HHV_{\mathrm{F}}} . \tag{11}$$

The cold gas efficiency shows the fraction of the chemical energy of the gasifier feed that is available in the syngas. This efficiency considers only the chemical energy of the syngas. The cold gas efficiency has limited usefulness since it neglects the physical exergy of the syngas.

1.1.3. Steam Reformer

Steam reforming is a catalytic conversion of hydrocarbons and steam by an endothermic reaction with steam into hydrogen $\mathrm{H_2}$ and carbon monoxide CO. This is the most common industrial process for producing hydrogen or hydrogen/carbon monoxide mixtures used in the synthesis of chemicals such as methanol or ammonia, in oil refining, and in many other chemical industrial processes. Natural gas (consisting primarily of methane CH_4) is often used as feedstock for the steam reforming process. The required thermal energy for driving the endothermic reaction is usually supplied through the combustion of a fossil fuel (Figure 3).

The mass, energy, entropy, and exergy balances for a control volume enclosing the reformer are

$$\dot{m}_1 + \dot{m}_2 - \dot{m}_3 = 0 \quad ; \quad \dot{m}_4 + \dot{m}_5 - \dot{m}_6 = 0 \tag{12}$$

$$\dot{H}_3 - (\dot{H}_1 + \dot{H}_2) - \dot{Q}_\mathrm{L} = (\dot{H}_4 + \dot{H}_5) - \dot{H}_6 \tag{13}$$

$$\dot{S}_\mathrm{gen,r} = [\dot{S}_3 - (\dot{S}_1 + \dot{S}_2)] + [\dot{S}_6 - (\dot{S}_4 + \dot{S}_5)] - \frac{\dot{Q}_\mathrm{L}}{T_\mathrm{b}} \tag{14}$$

$$\dot{E}_\mathrm{D,r} = \underbrace{(\dot{E}_4 + \dot{E}_5 - \dot{E}_6)}_{\dot{E}_\mathrm{F,r}} - \underbrace{(\dot{E}_3 - \dot{E}_1 - \dot{E}_2)}_{\dot{E}_\mathrm{P,r}} \tag{15}$$

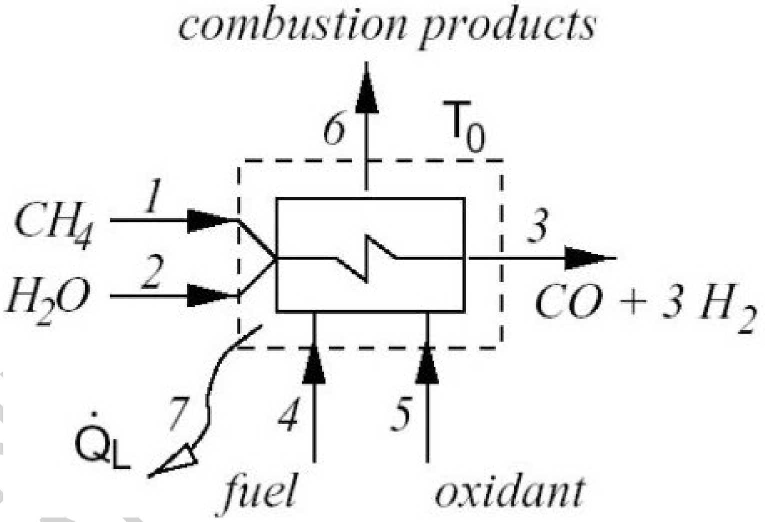

Figure 3: Steam reformer.

The main thermodynamic inefficiencies in the reformer are associated with the chemical reactions (steam reforming and combustion) and heat transfer from the combustion products to the hydrocarbon/water-mixture in the tubes. The exergy destruction caused by the combustion reaction is significantly higher than the exergy destruction due to the reforming reaction.

Measures to improve the efficiency of combustion processes are discussed in Section 1.1.1. The exergy destruction associated with the reforming reaction can be reduced by preheating the hydrocarbon and the steam and by mixing the reactants at equal temperature and pressure. Friction and heat losses also contribute to the thermodynamic inefficiencies.

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Biographical Sketches

Professor Tsatsaronis is the Bewag Professor of Energy Conversion and Protection of the Environment and the Director of the Institute for Energy Engineering at the Technical University of Berlin, Germany. He studied mechanical engineering at the National Technical University of Athens, Greece, receiving the Diploma in 1972. He continued at the Technical University of Aachen, Germany, where he received a Masters Degree in business administration in 1976, a Ph.D. in combustion from the Department of Mechanical Engineering in 1977, and a Dr. Habilitatus Degree in Thermoeconomics in 1985.

In the last twenty five years he has been responsible for numerous research projects and programs related to combustion, thermoeconomics (exergoeconomics), development, simulation and analysis of various energy-conversion processes (coal gasification, electricity generation, hydrogen production, cogeneration, solar energy-conversion, oil production in refineries and also from oil shale, carbon black production, etc) as well as optimization of the design and operation of energy systems with emphasis on power plants and cogeneration systems.

He is a Fellow of the American Society of Mechanical Engineers (ASME) and a member of the American Institute of Chemical Engineers, the German Association of University Professors and the Greek Society of Engineers. He is the Past Chairman of the Executive Committee of the International Centre for Applied Thermodynamics.

In 1977 he received for his Ph.D. Thesis the Borchers Award from the Technical University of Aachen, Germany and in 1994 and 1999 the E.F. Obert Best Paper Award from ASME. In 1997 he became a Honorary Professor at the North China Electric Power University and in 1998 he received from ASME the James Harry Potter Gold Medal for his work in exergoeconomics.

He currently serves as an associate editor of *Energy - The International Journal* (since 1986), *Energy Conversion and Management* (since 1995), *International Journal of Applied Thermodynamics* (since 1998), and *International Journal of Energy, Environment and Economics* (since 2001). He co-authored with A. Bejan and M. Moran the book *Thermal Design and Optimization* and published over 150 papers.

Dr. Frank Cziesla is Senior Research Associate and Lecturer at the Institute for Energy Engineering, Technical University of Berlin, Germany. He received the Diploma in Chemical Engineering from the Technical University of Berlin in 1994. In the same year, he joined the Institute for Energy Engineering as a research associate. His research activities on the design of cost-effective energy conversion systems using exergy-based optimization techniques and knowledge-based approaches led to the Ph.D. degree in 1999. He spent the summer of 1997 at the School of Nuclear Engineering, Purdue University (USA) working on a combination of exergy-based optimization techniques and fuzzy systems.

His current research activities focus on the design and operation of cost-effective energy conversion systems using exergy-based analysis and optimization techniques (thermoeconomics) as well as principles taken from the fields of artificial intelligence (experts systems) and computational intelligence (fuzzy systems, evolutionary algorithms).

He lectures on energy engineering, power plant technology, thermal design and optimization as well as applications of computational intelligence in energy engineering.

Dr. Cziesla is a member of the German Association of Engineers (VDI, Verein Deutscher Ingenieure) and the Society for Chemical Engineering and Biotechnology (DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie e.V.).