

Lecture 7 Introduction to Exergy Analysis: Loss Theory and Marginal Process Efficiency

Goal of the lecture: To study the concept of exergy, its application in evaluating energy losses, and to understand the theory of irreversibility and marginal efficiency in thermodynamic processes.

Brief lecture notes: This lecture introduces the concept of exergy — a measure of the useful or available portion of energy that can be converted into work. Unlike energy, which is conserved, exergy is destroyed due to irreversibilities such as friction, heat transfer through finite temperature differences, and chemical reactions. The lecture explains the principles of exergy balance, loss theory, and marginal process efficiency, which together provide a powerful framework for analyzing and optimizing real thermodynamic systems such as power plants, turbines, compressors, and heat exchangers. Emphasis is placed on understanding where and why losses occur, and how minimizing exergy destruction leads to more sustainable and efficient engineering designs.

Main part

Exergy represents the maximum useful work that can be obtained from a system as it comes into equilibrium with its environment. It is sometimes called the available energy or availability. Unlike energy, exergy is not conserved — it is destroyed whenever irreversibilities occur. The general idea can be summarized as:

Energy is conserved; Exergy is consumed.

The total energy of an isolated system remains constant, but the quality of that energy, as measured by exergy, decreases due to entropy generation.

Reference Environment and Exergy Components

All exergy analyses require a reference environment — a hypothetical large reservoir characterized by constant temperature T_0 , pressure P_0 , and chemical composition. The exergy of a system can be decomposed into several components: For most engineering systems, physical exergy is dominant and is expressed as:

$$E_{ph} = (h - h_0) - T_0(s - s_0)$$

where h and s are the specific enthalpy and entropy of the system, and h_0 , s_0 are those at the reference environment.

Exergy Balance and Destruction

The exergy balance for an open steady-flow system can be written as:

$$\dot{E}_{in} - \dot{E}_{out} = \dot{E}_{dest}$$

where

- $\dot{E}_{in}$ — exergy entering with heat, work, and mass flow,
- $\dot{E}_{out}$ — exergy leaving the system,
- $\dot{E}_{dest}$ — exergy destruction due to irreversibilities.

Exergy destruction is directly related to entropy generation:

$$\dot{E}_{dest} = T_0 \dot{S}_{gen}$$

This fundamental relation connects the second law of thermodynamics with practical performance evaluation. The greater the entropy generation, the greater the exergy loss and the lower the system efficiency.

Loss Theory

Loss theory provides a systematic way to quantify inefficiencies in thermodynamic systems. Every real process involves losses — portions of energy that cannot be converted into useful work due to irreversibility. According to this theory, losses are measured not by energy that disappears, but by exergy that is destroyed.

Sources of exergy loss include:

- Friction and viscous dissipation,
- Non-equilibrium heat transfer,
- Pressure drops in pipes and valves,
- Mixing of fluids at different states,
- Chemical reaction irreversibilities.

By analyzing where exergy destruction occurs, engineers can target process improvements more effectively than by using only first-law (energy) analysis.

Marginal Process Efficiency

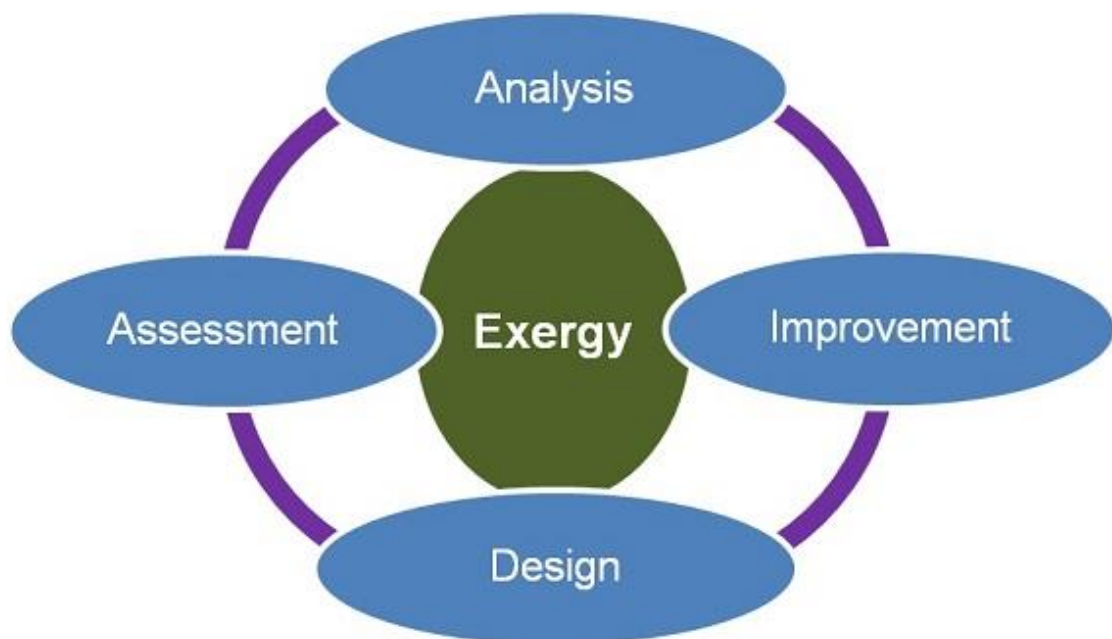
Marginal process efficiency evaluates how efficiently a process converts *incremental inputs* of exergy into useful work or products. It is defined as the ratio of the useful exergy output to the total exergy input:

$$\eta_{ex} = \frac{\text{Useful Exergy Output}}{\text{Total Exergy Input}} = 1 - \frac{\dot{E}_{dest}}{\dot{E}_{in}}$$

This measure reflects not only how much energy is transformed but also how effectively it is used. High marginal exergy efficiency means that few resources are wasted, and system performance is close to the ideal reversible limit.

Visualization of Exergy Flows

Figure 1. Exergy flows in a thermodynamic system.



Typical Exergy Loss Distribution

System Component	Typical Exergy Destruction (%)	Main Source of Loss
Combustion chamber	25–40	Chemical reaction irreversibility
Turbine	10–20	Friction, fluid expansion losses
Compressor	5–10	Compression inefficiency
Heat exchanger	10–25	Finite temperature difference
Condenser	5–15	Heat rejection at low temperature

Such analysis helps prioritize which components to redesign for better thermodynamic performance.

Engineering Significance

Exergy analysis bridges the gap between theoretical thermodynamics and real-world energy systems. It allows engineers to:

- Identify where energy degradation occurs,
- Quantify inefficiencies as exergy destruction,
- Compare different processes on a common basis,
- Develop strategies for process optimization and sustainability.

Unlike energy efficiency, which only measures the quantity of energy used, exergy efficiency reveals the *quality* and *usefulness* of energy transformations. Therefore, it is a cornerstone of modern energy system analysis and sustainable design.

Questions for Self-Control

1. What is the main difference between energy and exergy?
2. How is exergy destruction related to entropy generation?
3. What is the physical meaning of the term “loss” in loss theory?
4. How can marginal exergy efficiency be used to evaluate system performance?
5. Why is exergy analysis more informative than first-law analysis alone?

Literature

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