Chapter 1

Introduction

Classical thermodynamics provides the concept of energy, energy transfer by heat and work, energy balance, entropy and entropy balance and calculations of thermodynamic properties at equilibrium. The second law of thermodynamics enhances an energy balance by calculating the true thermodynamic value of an energy career and real thermodynamic inefficiencies and losses from the process and system. Exergy is the maximum useful work attainable from an energy career under the given environmental conditions. The exergy of an energy carrier is a thermodynamic property that depends on both the state of the carrier being considered and the state of the environment. It expresses the maximum capability of the energy carrier to cause changes. Thus, exergy is closely related to the economic value of the carrier because users pay for the potential of energy to cause changes. When costs are assigned to energy carriers, exergy should serve as a basis in the costing process.

Conventionally, first law analysis gives only energy utilization scenario in terms of conservation of energy. But it cannot provide the information regarding the losses both qualitatively and quantitatively and cannot find the location of these losses. These limitations force us to go for exergy analysis based on second law of thermodynamics. Exergy is not a conserved property but some of it is destroyed in the real process. Exergy analysis gives uniform base for comparison of various thermodynamic processes. This analysis proves the information regarding losses including their location qualitatively and quantitatively. This information can be used for further improvement in the design and operation of the system. By locating the exergy destruction, the system performance can be improved by improving the exergetic efficiency of the component and the system.

Unlike total energy, a part of the total exergy supplied to a system is irreversibly destroyed in all real processes. This exergy destruction is the direct result of the irreversibilities in a system and usually represents the largest part of 'energy waste'. The other part of 'energy waste' is the exergy loss, i.e. the exergy associated with a material or energy stream rejected to the environment (e.g. flue gas, cooling water and heat loss). The exergy loss is associated with the design engineer's decision to not further use the exergy of a stream in a given system. Malfunctioning and off-design performance of a component usually increases both the exergy destruction and the exergy losses in a system. A part of the exergy destruction and exergy loss is dictated by considerations involving costs, environmental impact, availability, and operability of the system being considered. In a truly optimized system, the entire amount of exergy destruction and loss is justifiable through these considerations. Both exergy destruction and exergy loss are identified through an exergy analysis (second-law analysis).

The term exergy was coined by Rant as a new word for 'work capability' used previously by Bosnjakovic. This term has gained general acceptance in all countries except the United States where the parallel use of the terms exergy and availability (available energy) continues to contribute to some misconceptions and confusion surrounding the exergy method. However, the word exergy finally prevailed in the United States too. Although the method of exergy is often considered to be a new method for analyzing energy systems, the underlying fundamentals were introduced in the last century following the mathematical formulation of the second law of thermodynamics. As outlined in the critical historical review by Tsatsaronis [1], the earliest contributions to the exergy concept are due to Clausius, Tait, Thomson, Gibbs and Maxwell. This early work, as well as the subsequent developments by Gouy, Stodola, Goudenough and Darrieus generated interest in exergy.

The modern development of exergy analysis was initiated by Bosnjakovic in Europe and Keenan in the United States. The classical slogan "Fight the Irreversibilities" by Bosnjakovic marks the beginning of this development. In the1950s and 1960s, contributions to the exergy concept were also made by Rant, Grassmann, Brodyansky, Bruges, Tribus, Obert, Gaggioli, Evans, Baehr, Fratzscher, Szargut, Petela and Knoche, among the others. During this period, the exergy balance and its graphical presentation, the calculation of the exergy of fuels and the definition of reference states for calculating the chemical exergy were introduced. In addition, several definitions of exergetic efficiencies and the first exergy-analysis applications to industrial processes and plants were presented. At the same time, the method of exergy analysis was introduced into the textbooks of thermodynamics. In the last twenty years, the annual number of worldwide exergy applications to various systems and processes has increased exponentially.

Formerly the term 'thermoeconomics' has been used to indicate an appropriate combination of exergetic and economic analysis in which the cost is assigned to the exergy (not the energy) content of an energy carrier (exergy costing). In parallel, however, the term 'thermoeconomic analysis' has been used by others to report conventional thermodynamic analyses based only on the first law of thermodynamics and economic analyses conducted separately from the thermodynamic ones and without the consideration of exergy or exergy costing. But 'thermo', is a derivative of the Greek word for heat and is used in most major languages. Thus, thermoeconomics does not imply exergy costing or exergy economics, but a combination of heat and economics.

The idea of using exergy for costing purposes was initiated by Keenan in 1932. His suggestion was not to apply exergy costing, but to use exergy for appropriately apportioning costs to the electric power and steam that were produced in a cogeneration plant. He pointed out that the economic value of steam and electricity lay in their exergy not energy. In 1949, Benedict presented the costing of exergy destruction in an air-separation plant and the use of these costs for 'optimal design'.

Along with the thermodynamic analysis, economic analysis gives the information regarding fixed cost e.g. investment cost, running cost, and operation and maintenance cost. In most of the cases, the overall cost of the system will increase with the increase in the system exergetic efficiency and capacity. Thus thermodynamic improvement in a system is accompanied by an increase in the economic cost. Therefore the system should be optimized between these two conflicting requirements. In this regard, thermoeconomic analysis evolved which bring thermodynamic and economic parameters in to one common platform and combines thermodynamic analysis with economic analysis. As discussed above, exergy analysis is preferred for thermodynamic analysis; the newly evolved field is called exergoeconomic analysis.

The development of thermoeconomics was initiated in the late 1950s by Tribus and Evans at the University of California, Los Angeles, and by Obert and Gaggioli at the University of Wisconsin, Madison. Tribus and Evans were applying the exergy concept to desalination processes when they introduced the word thermoeconomics, developed the idea of assigning costs to the exergy unit of streams, and formulated cost balances at the component level of energy systems. Obert and Gaggioli applied exergy costing to the optimal selection of steam piping and its insulation. In Europe, Bergmann and Schmidt assigned costs to the exergy destruction in each component of a steam power plant in a study dealing with optimization of feed water heaters. Fratzscher and Kloiditz referred to the early work of Evans and Tribus applied exergy costing to the design of a regenerative heat exchanger. Szargut used exergy costing in a cogeneration plant. In 1970 El-Sayed and Evans marked the introduction of rigorous calculus methods of optimization in thermoeconomics. In 1980, Evans [2] thermoeconomically isolated the components of thermal system from each other and expressed the interactions in terms of essential or useful energy which he called "Essergy" and described all economic interaction by Lagrange multiplier. This approach, though it has not yet yielded the expected practical results, continues to show promise.

In 1985, Tsatsaronis and Winhold [3] coined the term 'exergoeconomics' to give a more precise combination of an exergy analysis with an economic analysis. The thermodynamic and economic analyses do not have to be combined in the more general field of thermoeconomics, whereas in exergoeconomics, they are integrated through exergy costing. Consequently, exergoeconomics is a part of thermoeconomics. A complete thermoeconomic analysis consists of (a) a detailed exergy analysis, (b) an economic analysis conducted at the component level of the energy system being analyzed, (c) exergy costing and (d) an exergoeconomic evaluation of each system component. The objectives of an exergoeconomic analysis are:

- To identify the location, magnitude and source of the real thermodynamic losses (energy waste) in an energy system (exergy destruction and exergy losses).
- To calculate the cost associated with the exergy destruction and exergy losses.

- To assess the production costs of each product (output) in an energy-conversion system that has more than one product.
- To facilitate feasibility and optimization studies during the design phase for an energy system, as well as process improvement studies for an existing system.

The exergoeconomic methods help in the system improvement using thermodynamic as well economic points of view by simultaneous modeling of thermodynamic and economic aspects of the system and its components. These methods are based on optimization technique, which search all possible solutions for the optimum design and operation of the system and its components. Just like the exergoeconomic analysis, exergoeconomic optimization also combines thermodynamic and economic aspects. For thermodynamic optimization based on exergetic consideration, two methodologies are identified, entropy generation minimization method and exergy destruction method.

The objective in the application of the entropy generation minimization (EGM) method is to find design in which the entropy generation is minimal. A minimum entropy generation design characterizes a system with minimum destruction of exergy. This method consists of dividing the system in to sub systems those are in local (or internal) thermodynamic equilibrium. Entropy is generated at the boundaries between sub systems, as heat and mass flow through the boundaries. Using these flow rates, the total rate of entropy generation is calculated in relation to the physical characteristics of the systems. The total entropy generation is then monitored and minimized by properly varying the physical characteristics of the systems.

In exergy destruction method (EDM), the exergy balance is to be carried out which states that the total exergy increase or decrease within the system boundary plus the exergy destruction within the same boundary equals the difference between the total exergy transfers in and out across the boundary. The exergy transfer across the boundary includes exergy transfer associated with the transfer of heat, work and mass entering and leaving the boundary across the boundary. This method gives the idea about the exergy loss and exergy destruction in the components. After analyzing all the components individually, the overall system performance can be estimated. Then by varying the system parameters, system can be optimized.

In exergoeconomics, a system and its components are thermodynamically based on exergy as well as economically analyzed to formulate an objective function which would satisfy the thermodynamic and the economic objectives of the system simultaneously. The thermodynamic objective is to maximize the exergetic efficiencies of the components and the system, and the economic objective is to minimize the investment cost, operation and maintenance cost of the system. Thus the objective of thermoeconomics is to obtain the compromise between these two competing objectives. In this methodology, appropriate costs are assigned to the thermodynamic inefficiencies of the system components through some meaningful fuel-product definition. For maximum exergetic efficiencies, these costs are to be minimized. The overall objective function for the system is defined so as to minimize the summation of the costs associated with the thermodynamic inefficiencies and other economic costs.

1.1 Exergoeconomic Methodologies

Many exergoeconomic analysis and optimization methodologies are developed in the last few decades by various researchers. They can be listed as below:

- Thermoeconomic Evaluation and Optimization Method
- Exergetic Cost Theory
- Thermoeconomic Functional Analysis
- Autonomous Method
- Structural Method
- Evolutionary Programming Method
- Extended Exergy Accounting Method
- Exergetic Production Cost Method

The detailed information regarding the development of these methodologies is given in the subsequent chapter on literature survey. In each methodology, mentioned above, has specific field of application for which it provides proven and efficient solution. All these methodologies are based on local optimization of the components after separation of the system components and then finding the overall solution for the whole system.

Exergoeconomic analysis and optimization, thus, is a very important step before the design, installation and commissioning of any energy intensive process plant. Nowadays, it has become an integral part of the plant design procedure for any thermal, chemical or petro-chemical process plants. A number of analysis and optimization models are suggested by various investigators in the recent past to carry out exergoeconomic analysis on thermally intensive systems such steam power plants, gas turbine power plants, combined cycle power plants, refrigeration systems such as vapour compression and vapour absorption systems, cryo-generation plants, internal combustion engines, hydrogen combustion process etc. Amongst the various thermal systems used for the development of analysis and optimization tools, vapour absorption refrigeration system seems to be attractive as it is a heat energy intensive system. Thus, an industrial AAVAR system used to generate chilled brine for industrial application in a fertilizer plant is exergoeconomically optimized using a hybrid method developed based on various methods suggested by earlier investigators.

1.2 Organization of the Thesis

The thesis is divided in to seven chapters. In the present chapter, the general area of exergoeconomic optimization is introduced and the development in the area of exergy and exergoeconomic analyses and optimization are briefly discussed. Chapter 2 gives an extensive review of open literature in the area of exergy analysis and optimization and exergoeconomic analysis and optimization. Based on the review, the current research area and problem are identified. A large capacity brine chilling unit working with AAVAR system of a large fertilizer plant with independent boiler as a heat source is selected as a case for developing the exergoeconomic optimization method. As the other option for heat source, steam generated at HRSG of gas turbine power plant and tapped steam from regenerative steam turbine power plant is selected. It is followed by the objectives of the present research work. The description of the AAVAR system, gas turbine power plant with HRSG and regenerative steam turbine power plant is given in Chapter 3. The exergoeconomic analysis chosen for the present optimization study is mainly based on Thermoeconomic Evaluation and Optimization (TEO) method