Chapter 2

Review of Literature

This chapter is concerned with review of literature on exergy and exergoeconomic analysis carried out on various thermal systems. The review is carried out primarily to develop an exergoeconomic tool for optimization of a brine chilling unit working on AAVAR system drawing heat energy from a dedicated boiler of a large fertilizer plant. The chapter is organized in three sections. The literature on various investigation using two types of exergy analysis, viz., entropy generation minimization method and exergy destruction method are separately given in Section 2.1. The section deals with the exergy analysis of various thermal systems in general and refrigeration systems in particular. Section 2.2 deals with the short discussion on various models developed by earlier investigators on exergoeconomic optimization. Based on the review, scope for the present investigation is identified and given in Section 2.3.

2.1 Exergy Analysis of Thermal Systems

The literature on exergy analysis using entropy generation minimization method (EGM) employed on various thermal systems such as vapour absorption refrigeration systems, vapour compression refrigeration systems, transcritical carbon dioxide refrigeration cycle, adsorption cycles, heat exchangers, radial fin geometry thermal energy storage systems, power plant, compression ignition engine and hydrogen combustion process are reviewed in Section 2.1.1. Section 2.1.2 deals with review of literature on exergy analysis using exergy destruction method (EDM) employed on various thermal systems. Both the sections are further divided in to two based on the literature on (i) refrigeration systems such as vapour absorption, vapour compression and transcritical refrigeration cycle etc. and (ii) other thermal systems such as heat exchangers, thermal storage systems, power plant, compression ignition engine etc.

2.1.1 Entropy Generation Minimization (EGM) Method

The objective in the application of the entropy generation minimization method is to find the design in which the entropy generation is minimum. A minimum entropy generation design characterizes a system with minimum destruction of exergy. This method consists of dividing the system in to sub systems which 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.

2.1.1.1 Refrigeration Systems

In 1995, Bejan et al. [4] applied the entropy generation minimization technique to absorption refrigeration system and found the way of dividing a finite supply of heat exchanger surface between the three heat exchangers of the refrigeration plant namely generator, condenser and evaporator for maximizing the cooling load at evaporator.

Talbi et al. [5], in 2000, carried out modeling, thermodynamic simulation and second law analysis through entropy generation minimization method for LiBr/Water VAR system. They quantified the irreversibility of each component of the chiller to determine the potential for each component to contribute to overall system exergy efficiency. The second law analysis of thermodynamics was applied and showed that the absorber, solution heat exchangers, and condenser have the most potential to improve chiller exergy efficiency.

In 2004, Ezzine et al. [6] carried out similar studies for ammonia-water double-effect, double-generator VAR system. In the same year, Adewusi et al. [7] carried out second law based thermodynamic analysis of AAVAR system. The entropy generation at each salient point and the total entropy generation S_{tot} of all the system components as well as the coefficient of performance of the system are calculated from the thermodynamic properties of the working fluids at various operating conditions. The results showed that the two stage system has a higher S_{tot} and COP, while the single-stage system has a lower S_{tot} and COP. This controversy is explained with respect to the performance results for both single and two-stage systems.

Kaynakli [8], in 2008, applied the entropy generation minimization method to the coil absorber of the LiBr absorption refrigeration system and determined the variation of the second law efficiency with cooling water flow rate, solution flow rate, cooling water temperature and solution concentration. The influence of absorber performance parameters is examined on the basis of the first and second laws of thermodynamics for parallel and counter-current types. In this regard, the heat and mass transfer, the second law efficiency, the magnitude and place of exergy losses in two types of absorbers are estimated and discussed comprehensively. The results showed that increasing the cooling water flow rate and decreasing the cooling water inlet temperature increase the heat and mass transfer, and decrease the second law efficiency. The effect of the solution concentration on the efficiency in general is small whereas the irreversibility for the counter-current mode is greater than that of the parallel-current mode.

In 2002, Yumrutas et al. [9] used entropy generation minimization method for the exergy analysis of vapour compression refrigeration (VCR) system using ammonia as refrigerant, and investigated the effects of the evaporating and condensing temperatures on the pressure losses, the exergy losses, the second law of efficiency, and the coefficient of performance (COP) of the cycle. It is found that the evaporating and condensing temperatures have strong effect on the exergy losses in the evaporator and condenser and on the second law of efficiency and COP of the cycle but little effects on the exergy losses in the compressor and the expansion valve. The second law efficiency and the COP increases, and the total exergy loss decreases with decreasing temperature difference between the evaporator and refrigerated space and between the condenser and outside air.

In 2005, Yang et al. [10] performed comparative study for the transcritical carbon dioxide refrigeration cycles with a throttling valve and with an expander, using entropy generation minimization method. The effects of evaporating temperature and outlet temperature of gas cooler on the optimal heat rejection pressure, the coefficients of performance, the exergy losses, and the exergy efficiencies are investigated. In order to identify the amounts and locations of irreversibility within the two cycles, exergy analysis is employed to calculate the entropy change and irreversibility through the Guy-Stodola's law, to analyze the thermodynamics process in each component. It is found that in the throttling valve cycle, the largest exergy loss occurs in the throttling valve.

Sarkar et al. [11], in 2009, carried out exergy analyses, with entropy generation minimization method, of evaporator and gas cooler of a CO_2 based transcritical heat pump for combined cooling and heating, employing water as the secondary fluid. Optimization of heat exchanger tube diameter and length and effect of design parameters on overall system performance is also presented. It is observed that higher heat transfer coefficient can be achieved by reducing the diameter only to a limited extent due to rapid increase in pressure drop. The minimum possible diameter depends on mass flow rate (capacity) and division of flow path. The right combination of optimum diameter and length depends on the number of passes, capacity and operating parameters. It is to be noticed that due to higher pressure drop occurring in the evaporator compared to the gas cooler, zero temperature approach is attained before the optimum length is reached in case of the evaporator. Presented results are helpful in choosing the effective heat exchanger size in terms of diameter, length and number of passes.

2.1.1.2 Other Thermal Systems

Other thermal systems that are analyzed by various investigators using EGM are adsorption cycles, heat exchangers, radial fin geometry thermal energy storage systems, power plant, compression ignition engine, hydrogen combustion process. They are reviewed in this section

Adsorption Cycles

Pons [12], in 1996, developed the second law analysis of the adsorption cycles with thermal regeneration. The different heat transports between heat transfer fluid and adsorbent, between adsorbent and condenser/evaporator heat sources, and between heat transfer fluid and heat sources are analyzed. The entropy balance is then completely established. Consistency between the first law and second law analysis is verified by the numerical values of the entropy productions. The optimal operation of an adsorber is then described, and the study of those optimal conditions leads to some correlation between the different internal entropy productions.

Heat Exchangers

In 1997, Cornelissen et al. [13] carried out an exergetic optimization of a heat exchanger by combining entropy generation minimization method and the life cycle analysis (LCA). The methodology in the LCA includes the effects of all the phases of the production, use and recycling on the environment by using only one criterion, to minimize the life cycle irreversibilities due to frictional pressure drops and the temperature difference between the hot and cold stream and irreversibilities due to the production of the materials and the construction of the heat exchanger associated with the delivery of domestic hot water while the other factors like pollution of air and water, noise etc are neglected. The analysis gives the design conditions of the heat exchangers which lead to the lowest life cycle irreversibility.

In 2007, Gupta et al. [14] carried out second law analysis of cross flow heat exchangers in the presence of non-uniformity of flow by developing the analytical model for exergy destruction. Entropy generation due to finite temperature difference and due to fluid friction is calculated and thereby the rise in the irreversibility is found. Their results bring out the reason behind the maximum entropy paradox in heat exchangers, the proper perspective of exergy destruction and the consequent optimization of cross flow heat exchangers from the second law viewpoint.

Taufiq et al. [15], in 2007, found the optimal thermal design of radial fin geometry having the heat interaction by convection, through the second law analysis using entropy generation minimization technique. The analysis involves the achievement of a balance between the entropy generation due to heat transfer and entropy generation due to fluid friction. The entropy generation rate is discussed and optimum thickness for fin array is determined on the basis of entropy generation minimization subjected to the global constraint. In addition, the influence of cost parameters on the optimum thickness of fin array is also considered. It has been found that the increase in cross flow fluid velocity will enhance the heat transfer rate that will reduce the heat transfer irreversibility.

In 2008, Wang et al. [16] applied the entropy generation method on the irreversibility of rotary air preheater in thermal power plant. Through the exergy analysis, the relationship between the efficiency of the thermal power plant and the total process of irreversibility in the rotary air preheater is built up. The major contributions of the entropy generation rate compared to the total irreversibility expressed in the entropy are identified: the entropy generation rate by heat transfer between air and gas, the entropy generation rate by the mixing of the exhaust gas with ambient, and the entropy generation rate by the pressure loss caused by friction. The various parameters like rotor height, channel ratio, leakage factor, leakage factor distribution and flow rate are considered as decision variables and by parametric variation, their effect on entropy generation rate and exergetic efficiency is analyzed.

Thermal Storage Systems

In 1999, Zubair et al. [17] applied the entropy generation minimization method to a sensible heat thermal energy storage system. They calculated the irreversibilities in the system in terms of entropy generated and appropriate monetary values are attached to the irreversible losses caused by the finite temperature difference heat transfer and pressure drop in the system. Including the other cost, they developed a new cost function called cost rate number and tried to minimize the cost by optimization.

Erek et al. [18], in 2008, used entropy generation minimization technique to analyze a latent heat storage system (around a cylindrical tube of shell and tube heat exchanger) during charging process. The numerical model of heat transfer fluid, pipe wall and phase change material for different parameters (shell radius and pipe length, *Re* number, inlet temperature of fluid etc.) is solved and extensive parametric studies are conducted to investigate how the solidification fronts, heat stored, heat transfer rates, entropy generation number and exergy efficiency change with time.

Heat Recovery Steam Generators

In 2007, Butcher et al. [19] carried out exergy analysis for waste heat recovery based power generation system. The temperature profiles across the heat recovery steam generator (HRSG), net work output, second law efficiency and entropy generation number are simulated for various operating conditions. The effect of pinch point on the performance of HRSG and on entropy generation rate and second law efficiency are also investigated. They observed that the second law efficiency of the HRSG and power generation system decreases with increasing pinch point. Moreover they observed that the first and second law efficiency of the power generation system varies with exhaust gas composition and with oxygen content in the gas. Their results provides the information on the role of gas composition, specific heat and pinch point influence on the performance of a waste heat recovery based power generation.

Compression Ignition Engine Using Biodiesel as Fuel

In 2007, Azoumah et al. [20] used entropy generation minimization method to optimize the performance of a compression ignition engine using bio-fuels such as cotton seed and palm oils, pure or blended with diesel for different engine loads. The previous studies involving engine using bio-fuels have evaluated their performance based on their brake power, brake thermal efficiency, brake specific fuel consumption (BSFC) and gas emissions analysis. By doing so, thermal pollution is ignored and the real performance of the engines regarding the second law of thermodynamics is overlooked. Therefore the entropy change due to the dumping of the waste heat in to the environment is also considered and a trade-off zone of engine loads (60% and 70% of the maximum load) was established between the gas emissions (NO and CO_2) and the exergy efficiency for optimal performance of the CI engine.

Hydrogen Combustion

In 2008, Rakopoulos et al. [21] suggested that during combustion of hydrogen, the reaction is a combination of two relatively simple molecules into a more complicated one. While hydrocarbon combustion, during which relatively complex molecules are destroyed and a multitude of lighter fragments is produced in a process that obviously generates large amounts of entropy. Therefore, hydrogen and methane mixture is provided and exergy analysis is carried out in which the entropy generation is tested as a function of hydrogen content of the fuel. It is observed that with increasing hydrogen content, the irreversibility produced during combustion decreases as a percentage of total injected fuel availability, and the second-law efficiency increases.

Table 2.1 summarizes the various investigations reviewed. Amongst the various refrigeration systems analyzed by investigators, focus is found to be on vapour absorption systems as they are heat energy intensive systems.

Table 2.1 Summary of Investigations on Various Thermal Systems Using EGM

System	Investigators	Year	Remarks
Refrigeration Systems			
Vapour absorption refrigeration (VAR) systems	Bejan A, Vargas J V C & Sokolov M	1995	Found the way of dividing a finite supply of heat exchanger surface between generator, condenser and evaporator for maximizing the cooling load at evaporator.
	Talbi M M & Agnew B	2000	Quantified the irreversibility of each component of the chiller to determine the potential for each component to contribute to overall exergy efficiency of LiBr system.
	Ezzine N B, Barhoumi M, Mejbri K, Chemkhi S & Bellagi A	2004	Quantified the irreversibility of each component of the chiller to determine the potential for each component to contribute to overall exergy efficiency of aqua ammonia double effect absorption chiller.
	Adewusi S A & Zubair S M	2004	Showed that, for two stage aqua ammonia system has a higher entropy generation and coefficient of performance(COP), while the single-stage system has a lower entropy generation and COP
	Kaynakli O	2008	Determined the variation of the exergetic efficiency with cooling water flow rate, solution flow rate, cooling water temperature and solution concentration for coil absorber of the LiBr absorption system.
Vapour compression refrigeration(VCR)system	Yumrutas R, Kunduz M and Kanoglu M	2002	Investigated the effects of the evaporator and condenser temperatures on various losses and on the COP of the system
Transcritical carbon dioxide refrigeration cycle (heat pump)	Yang J L, Ma YT, Li M X & Guan H Q	2005	Investigated the effects of evaporating temperature and outlet temperature of gas cooler on the optimal heat rejection pressure, COP, the exergy losses, and the exergy efficiencies.
	Sarkar J, Bhattacharyya S & Gopal M R	2009	Presented CO_2 heat pump for combined cooling and heating application, optimization of heat exchanger tube diameter and length and presented the effect of design parameters on overall system performance.

Other Thermal Systems			
Adsorption cycle	Pons M	1996	Described the optimal operation of an adsorption cycle and presented optimal conditions leading to correlations between different internal entropy productions
Thermal energy storage system	Zubair S M and Al-Naglah M A	1999	Calculated irreversibility in a sensible heat storage system in terms of entropy generated and attached appropriate monetary values to the irreversible losses and tried to minimize the cost by optimization.
	Erek A and Dincer I	2008	Analyzed a latent heat storage system during charging process
Heat exchanger	Cornelissen R L and Hirs G	1997	Combined entropy generation minimization method and the life cycle analysis (LCA) and found the design conditions of the heat exchangers which lead to the lowest life cycle irreversibility.
	Gupta A and Das S K	2007	Calculated entropy generation due to finite temperature difference and due to fluid friction and found increase in the irreversibility for cross flow heat exchanger.
	Wang H Y, Zhao L L, Zhou Q T, Xu Z G and Kim H T	2008	Examined irreversibility in the rotary air preheater and analysed its effect on the efficiency of thermal power plant.
Radial fin geometry	Taufiq B N, Masjuki H H, Mahlia T M I, Saidur R, Faizul M S & Mohamad E N	2007	Found the optimal thermal design of radial fin geometry having the heat interaction by convection.
Heat Recovery Steam Generator	Butcher	2007	Presented, for waste heat recovery plant, the effect of pinch point on the performance of HRSG. Observed decrease in the second law efficiency and power generation rate for HRSG with increase in pinch point.
C I Engine using biodiesel as fuel	Azoumah Y, Blin J and Daho T	2007	Analyzed the performance of CI engine using various types of bio-fuels for various load conditions.
Hydrogen combustion process	Rakopoulos C D, Scott M A, Kyritsis D C and Giakoumis E G	2008	Showed that, with increasing hydrogen content, the irreversibility produced during combustion decreases as a percentage of total injected fuel availability, and the second-law efficiency increases.

2.1.2 Exergy Destruction Method (EDM)

An exergy balance 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. Exergy destruction method is based on the above observations. The various studies reported are reviewed in this section.

2.1.2.1 Refrigeration & Air-conditioning Systems

This section is devoted to the review of various studies carried out on various refrigeration systems, air-conditioning systems and combined refrigeration and other thermal systems using exergy destruction method.

Vapour Absorption Refrigeration Systems

In 1986, Alvares et al. [22, 23] simulated the AAVAR system and carried out exergy analysis using exergy destruction method. They tried to analyze the effect of generator temperature and evaporator pressure on exergetic COP and tried to optimize the system.

In 1990, Karakas et al. [24] carried out Second-Law analysis of Solar Absorption Cooling Cycles using LiBr/Water and Ammonia/Water as working Fluids. Ataer et al. [25], in 1991, studied the irreversibilities in components of AAVAR system like condenser, evaporator, absorber, generator, pump, expansion valves, mixture heat exchanger and refrigerant heat exchanger, by second law analysis. Pressure losses between the generator and condenser, and the evaporator and absorber are taken into consideration. The dimensionless exergy loss of each component, the exergetic coefficient of performance, the coefficient of performance and the circulation ratio are given graphically for different generator, evaporator, condenser and absorber temperatures. They concluded that the evaporator and absorber of the absorption refrigeration system are the components in which, within the given operating conditions, high exergy loss is observed and they should be modified to give a better system performance. For each condenser, absorber and evaporator temperature, there is a generator temperature at which the dimensionless total exergy loss of the system is a minimum. At this point, the COP and Exergetic Coefficient of Performance of the system are at a maximum. Consequently the results of the second law analysis can be used to identify the less efficient components of the system and also to modify them. Moreover, the suitability of the selected components can be judged by this analysis. The second law analysis may be a good tool for the determination of the optimum working conditions of such systems.

In 1995, Aphornratana et al. [26] provided the second law method as applied to a single-effect LiBr/Water VAR system. Exergy at each salient point is found and exergy analysis of each component is carried out and found the effect of variation of various parameters like generator temperature, solution heat exchanger effectiveness, solution circulation rate, evaporator temperature, and condenser temperature is analyzed.

In 1998, Ravikumar et al. [27] carried out exergy analysis of double effect LiBr/water VAR system. He showed the exergy variation across the individual component with respect to generator temperature and found the second generator more effective.

In 2004, Kilic et al. [28] developed mathematical model using exergy analysis for LiBr-Water VAR system. The effect of main system temperatures on the performance parameters of the system, irreversibilities in the thermal process and non-dimensional exergy loss of each component are analyzed. The results show that the performance of the absorption refrigeration system increases with increasing generator and evaporator temperatures, but decreases with increasing condenser and absorber temperatures.

In 2005, Sencan et al. [29] carried out exergy analysis of single-effect LiBr/water VAR system. Exergy loss, enthalpy, entropy, temperature, mass flow rate and heat rate in each component of the system are evaluated. They concluded that the condenser and evaporator heat loads and exergy losses are less than those of the generator and absorber. This is due to the heat of mixing in the solution, which is not present in pure fluids.

In 2008, Morosuk et al. [30] suggested a new approach to the exergy analysis of VAR machines. Exergy destruction in a component can be split into endogenous and exogenous parts. The endogenous part of exergy destruction, associated only with the irreversibility occurring within the component when all other components operate in an ideal way and the component being considered operates with its current efficiency. The exogenous part of exergy destruction within the component is caused by the irreversibility that occurs in the remaining components. These splitting enable engineers working in system optimization to estimate the exergy destruction in a component caused by the component itself on one hand and by the remaining components on the other hand. This information can be used to decide whether engineers should focus on the component being considered or on the remaining system components, in order to effectively improve the overall performance. Again the exergy destruction in a component can be divided in unavoidable and avoidable parts. The exergy destruction rate that cannot be reduced due to technological limitations such as availability and cost of materials and manufacturing methods is the unavoidable part of the exergy destruction. The remaining part represents the avoidable part of the exergy destruction. Thus, splitting the exergy destruction into unavoidable and avoidable parts in the component provides a realistic measure of the potential for improving the thermodynamic efficiency of a component. A conventional exergy analysis (without splitting the exergy destruction) would suggest that components should be improved in the following order: absorber (40.4%), generator (39.2%), condenser (16.4%) and evaporator (1.2%).But the information provided through the splitting of the exergy destruction shows that 65.8 % of the total exergy destruction within the absorption refrigeration system is unavoidable.

In 2008, Gomri et al. [31] carried out Second law analysis of double effect LiBr/water VAR system using exergy destruction method. It is observed that that the performance of the system increases with increasing low pressure generator (LPG) temperature, but decreases with increasing high pressure generator (HPG) temperature. The highest exergy loss occurs in the absorber and in the HPG, which therefore makes the absorber and HPG the most important components of the double effect refrigeration system.

Similar type of analysis of single effect and double effect LiBr/water VAR system is carried out by Gomri [32] in 2009. It is concluded that the COP of double effect system is approximately twice the COP of single effect system but the exergetic efficiency of double effect system increase slightly compared to the exergetic efficiency of single effect system. It is found that for each condenser and evaporator temperature, there is an optimum generator temperature where the total change in exergy of the single effect and double effect absorption refrigeration systems is minimum. At this point the COP and exergetic efficiency of the systems become maximum.

It should be noted that most of the studies are focussed on LiBr/ water VAR systems and few studies are reported on AAVAR systems.

Vapour Compression Refrigeration Systems

In 1987, Mastrullo et al. [33] conducted exergetic analysis of multi stage VCR systems using R12. Plant exergetic efficiencies, equipment irreversibility, and their sensitivity to main system parameters are evaluated for several typical component arrangements. The use of a flash tank for separation, desuperheater, and with a subcooling coil seemed the best solution.

In 1988, Kumar et al. [34] explained the method of carrying out an exergetic analysis on a vapour compression refrigeration system using R11 and R12 as refrigerants. Exergy-Enthalpy diagrams are presented for these two refrigerants which facilitate the analysis. The procedure to calculate the various losses occurring in different components, as well as the coefficient of performance and the exergetic efficiency of the refrigeration cycle, has been explained by means of a numerical example. In 1993, Lohlein et al. [35] did the exergy analysis of low temperature refrigerators for large scale cooling system and check variety of arrangements of component.

In 2002, Aprea et al. [36] compared VCR systems with R22 and R407C on the base of exergetic analysis and found that the overall exergetic performance of the plant working with R22 is consistently better.

In 2003, Srinivasan at el, [37] carried out exergetic analysis of carbon dioxide VCR cycle using the new fundamental equation of state and prepared temperature v/s exergy chart and enthalpy v/s exergy chart. There exist upper and lower bounds for the high cycle pressure for a given set of evaporating and pre-throttling temperatures. The maximum possible exergetic efficiency for each case was determined. Empirical correlations for exergetic efficiency and COP, valid in the range of temperatures studied, are obtained and the exergy losses are quantified. In 2004, Fartaj et al. [38] analyzed transcritical CO_2 refrigeration cycle. By exergy loss analysis they showed that the compressor and the gas cooler exhibit the largest non-idealities within the system.

In 2008, Dopazo et al. [39] has analyzed a cascade refrigeration system with CO_2 and NH_3 as working fluids in the low and high temperature stages, respectively using exergy destruction method. After calculating exergy flow at inlet and outlet of all the components, exergetic efficiency of the components and system is evaluated. The effect of parametric variation of various decision variables on COP and exergetic efficiency is found and subsequently the exergetic optimization of the system is carried out.

In 2009, Mafi et al. [40] exegetically analyzed the multistage cascade low temperature refrigeration systems having closed cycle propylene and ethylene systems, through exergy destruction method. Propylene refrigeration is utilized at several temperature levels to cool and heat the feed in the initial fractionation sections of the plant while the ethylene refrigeration is utilized at several temperature levels to cool the feed in the cryogenic section of the plant. The equations of exergy destruction and exergetic efficiency for the main system components such as heat exchangers, compressors and expansion valves are developed and combining them expression for minimum work requirement for the refrigeration systems is developed. It shows that the minimum work depends only on the properties of incoming and outgoing process streams cooled or heated with refrigeration system and the ambient temperature.

Air-Conditioning Systems

In 2002, Bilgen et al. [41] carried out exergy analysis of air conditioner system. The irreversibilities due to heat transfer and friction have been considered. The coefficient of performance based on the first law of thermodynamics as a function of various parameters, their optimum values, and the efficiency and coefficient of performance based on exergy analysis have been derived. Based on the exergy analysis, a simulation program has been developed to simulate and evaluate experimental systems. The simulation of a domestic heat pump air conditioner is then carried out using experimental data. It is found that COP based on the first law varies from 7.40 to 3.85 and the exergy efficiency from 0.37 to 0.25 both a decreasing function of heating or cooling load. The exergy destructions in various components are determined.

In 2009, Wei et al. [42] applied the exergy destruction method to Variable Air Volume type Air Conditioning system. Exergy of air volume is calculated by considering the humidity and partial pressure of water vapour in the air. Exergy efficiency is calculated considering the equivalent CO_2 emissions due to the generation of electricity used by the VAV system. It is found that the exergy efficiency is only 2-3% of potential work that can be developed by using these energy sources as supplied for satisfying the environmental thermal conditions for human occupancy and indoor air quality.

Combined Refrigeration and Other Thermal Systems

In 2006, Vidal et al. [43] performed exergy analysis for the combined power and refrigeration cycle, also known as Goswami cycle, in which the AAVAR system generates cooling and expansion of refrigerant take place in vapour turbine generates power. Through analysis, it is showed that the solar collectors or waste heat can be the best heat sources to operate the cycle.

In 2008, Dai et al. [44] proposed combined power and refrigeration cycle, which combines the Rankine cycle and the ejector refrigeration cycle, produces power output and refrigeration output simultaneously. An exergy analysis is performed and exergy destruction in each component is calculated. A parameter optimization is achieved by means of genetic algorithm to reach the maximum exergy efficiency. The results show that the biggest exergy loss due to the irreversibility occurs in heat addition processes, and the ejector causes the next largest exergy loss. It is also shown that the turbine inlet pressure, the turbine back pressure, the condenser temperature and the evaporator temperature have significant effects on the turbine power output, refrigeration output and exergy efficiency of the combined cycle.

In 2008, Khaliq [45] analyzed trigeneration system generating electricity, process heat and cooling effect. In the system, gas turbine cycle is combined with heat recovery steam generator and LiBr/water VAR system. The exhaust gas from gas turbine is supplied to heat recovery steam generator to generate process steam. The gas coming out of HRSG is supplied to the generator of LiBr/water VAR system to produce cooling effect. Applying the exergy destruction method, the effect of overall pressure ratio, turbine inlet temperature, pressure drop in combustor and heat recovery steam generator, and evaporator temperature on the exergy destruction in each component is investigated. It is observed 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. In 2009, Kelly et al. [46] applied the same concept to the VCR system and gas turbine system.

2.1.2.2 Other Thermal Systems

Various investigations carried out using EDM on other thermal systems such as various power plants, solar energy based systems, thermal storages systems, heat exchangers, bio mass gasifier, combustion process, cooling tower boilers and fuel cells are discussed in this section.

Power Generation Systems

Nag et al. [47] presented first and second law analysis of a combined cycle power plant using pressurized circulating fluidized beds for partial gasification and combustion of coal. They evaluated the effects of pressure ratio and peak cycle temperature ratio of the gas cycle and the lower saturation pressure of the steam cycle on the overall performance of the combined plant.

In 2006, Hamed et al. [48] applied the exergy destruction method to power/water cogeneration plant. They calculated the exergy destruction in each component and calculated the appropriate cost of it. They allocated the cost of exergy destruction and cost of various components to water and electricity production appropriately which he called direct cost allocation method and found minimum product cost.

In 2008, Abusoglu et al. [49] applied the exergy destruction method to the diesel engine powered cogeneration systems generating electricity and steam. After defining the fuel and product in terms of exergy flow for each component of the system and calculated the exergetic efficiency of them. It is observed that total exergy destruction in the engine is mostly due to the highly irreversible combustion process in the engine, heat losses from engine and friction.

In 2008, Rakopoulos [50] developed the zero-dimensional, multi-zone, thermodynamic combustion model based on second law analysis, by dividing the burned gas into several distinct zones, in order to account for the temperature and chemical species stratification developed in the burned gas during combustion, for the prediction of spark ignition (SI) engine performance and nitric oxide (NO) emissions. Total exergy including thermal, mechanical and chemical for fuel at each salient point is calculated. By applying the exergy balance method, the exergetic efficiency for each zone is calculated. By changing the air fuel ratio, it is revealed that the crucial factor determining the thermodynamic perfection of combustion in each burned zone is the level of the temperatures at which combustion occurs in the zone, with minor influence of the whole temperature history of the zone during the complete combustion phase.

In 2008, Som et al. [51] did the exhaustive review of the exergy analysis of combustion system. They defined the exergetic efficiency and rate of irreversibility for combustion system and using both method of exergy analysis; exergy balance and entropy generation minimization carried out the exergetic analysis of combustion system and compared the combustion of solid, liquid and gaseous fuel. They found that the major source of irreversibilities is the internal thermal energy exchange associated with high temperature gradients caused by heat release in combustion reactions and to reduce the exergy destruction in the combustion process, the irreversibility should be reduced through proper control of physical processes and chemical reactions resulting in a high value of flame temperature but lower values of temperature gradients within the system and optimum condition can be determined.

In 2008, Kanoglu et al. [52] performed exergy analysis of a binary geothermal power plant using exergy destruction method. Exergy destruction throughout the plant is quantified and illustrated using an exergy diagram, and compared to the energy diagram. The exergy and energy efficiencies are calculated for the entire plant and for the individual plant components. The sites of exergy destruction are identified and quantified. Also, the effects of turbine inlet pressure and temperature and the condenser pressure on exergy and energy efficiencies, the net power output and the brine reinjection temperature are investigated and the trends are explained.

In 2009, Aljundi [53] did energy and exergy analysis of a steam power plant in Jordan using exergy destruction method. The performance of the plant was estimated by a component wise modelling and a detailed break-up of energy and exergy losses. It shows that the thermal efficiency (26%) is low compared to modern power plants because this efficiency was not based on the specific heat input to the steam; rather, it was based on the lower heating value of the fuel to incorporate the losses occurring in the furnace-boiler system due to energy lost with hot gases, incomplete combustion, etc. It is observed that maximum exergy destruction is there in boiler and maximum exergy loss in condenser.

Kamate et al. [54], in 2009, analyzed cogeneration power plants in sugar industries through exergy destruction method for various steam inlet condition. The results shows that, at optimal steam inlet conditions of 61 bar and 475°C, the backpressure steam turbine cogeneration plant perform with energy and exergy efficiency of 0.863 and 0.307 and condensing steam turbine plant perform with energy and exergy efficiency of 0.682 and 0.260, respectively. Boiler is the least efficient component and turbine is the most efficient component of the plant.

Solar Energy Based Systems

In 2007, Gunerhan et al. [55] analyzed the solar water heating systems for building applications. The system consists of namely a flat plate solar collector, a heat exchanger (storage tank) and a circulating pump. In the analysis, the exergy destruction method is used and irreversibility as per the guy stodola's law is introduced. Using exergy and irreversibility, few parameters such as fuel depletion ratio, relative irreversibility, productivity lack, exergetic factor and exergetic improvement potential are defined. Exergy destructions (irreversibilities) as well as exergy efficiency relations are determined for each of the system components and the whole system. Exergy efficiency correlations for the solar collector are presented to determine its exergetic performance. The effect of varying water inlet temperature to the collector on the exergy efficiencies of the Solar Water Heating system components is investigated and presented in the form of an exergy efficiency curve similar to the thermal efficiency.

In 2009, Celma et al. [56] analyzed solar drying process through exergy analysis. Using the first law of thermodynamics, energy analysis was carried out to estimate the amounts of energy gained from solar air heater and the ratio of energy utilization of the drying chamber. Also, applying the second law, exergy analysis was developed to determine the type and magnitude of exergy losses during the solar drying process. It was found that exergy losses took place mainly during the second day, when the available energy was less used.

In 2008, Zhai et al.[57] carried out the exergy analysis using exergy destruction method, of a small scale hybrid solar heating, chilling and power generation system, including parabolic trough solar collector with cavity receiver, a helical screw expander and silica gel-water adsorption chiller and the power generation cycle at lower temperature level. It is found that both the main energy and exergy loss take place at the parabolic trough collector. The economical analysis in terms of cost and payback period has been carried out using life cycle cost analysis

(LCCA). In LCCA, costs are grouped into three categories, capital expense for equipment and installation, operation & maintenance and fuel costs, and costs are incurred in demolition and disposal of the system while the equipment can have some salvage value. It is observed that the payback period is about 18 years in the present energy price condition.

In 2010, Gupta et al. [58] applied exergy analysis to the direct steam generation solar–thermal power plant in which steam is generated in solar collector and expanded in steam turbine to generate power. It is found that the maximum exergy loss is in the solar collector field while in other plant components it is small. The application of exergy destruction method is found for conventional power plant either based on gas cycle or on steam cycle.

In 2010, Baghernejad et al. [59] carried out exergy analysis, by the same method, of an integrated solar combined cycle system. They identified the causes of exergy destruction and their numerical values for the various components like combustor, collector, heat exchangers, pump and turbines.

In 2008, Torchia-Nunez et al. [60] presented a steady-state and transient theoretical exergy analysis of a solar still, focused on the exergy destruction in the components of the still: collector plate, brine and glass cover. The energy balance for each component resulting in three coupled equations where three parameters—solar irradiance, ambient temperature and insulation thickness are studied. The energy balances are solved to find temperatures of each component; these temperatures are used to compute energy and exergy flows. It is observed that the irreversibilities produced in the collector account for the largest exergy destruction, whereas irreversibility rates in the brine and in the glass cover are negligible. For the same exergy input a collector, brine and solar still exergy efficiency are calculated.

In 2009, chow et al. [61] proposed the exergy analysis of photovoltaic thermal collector with and without glass cover. From the exergy analysis, the increase of PV cell efficiency, packing factor, water mass to collector area ratio, and wind velocity are found favourable to go for an unglazed system, whereas the increase of on-site solar radiation and ambient temperature are favourable for a glazed system.

In 2009, Farahat et al. [62] exegetically optimized flat plate solar collector through exergy destruction method. After calculating the exergy flows, losses and exergetic efficiency of flat plate solar collector, the exergetic optimization is carried out under given design and operating conditions and the optimum values of the mass flow rate, the absorber plate area and the maximum exergy efficiency have been found.

Various researchers [63 to 68] applied this tool to find the losses in the various component of power plant and tried to improve the performance of the same.

Miscellaneous Thermal Systems

In 2001, Yilmaz et al. [69] carried out exergy analysis of heat exchanger using EGM and EDM and compared the output of both the methods.

In 2007 Talens et al. [70] suggested the use of Exergy Flow Analysis as an environmental assessment tool to account wastes and emissions, determine the exergetic efficiency, compare substitutes and other types of energy sources: all useful in defining environmental and economical policies for resource use with the example of process of bio-diesel production. The results show that the production process has a low exergy loss. The exergy loss is reduced by using potassium hydroxide and sulphuric acid as process catalysts and can further be minimized by improving the quality of the used cooking oil.

In 2007, Ptasinski et al. [71] carried out exergetic analysis of biomass gasification plant. They compared different types of bio-fuels for their gasification efficiency and benchmark against gasification of coal. In order to quantify the real value of the gasification process exergy-based efficiencies, defined as the ratio of chemical and physical exergy of the synthesis gas to chemical exergy of a bio-fuel, are proposed.

In 2008, Toonssen et al. [72] applied the exergy destruction method to hydrogen production plant based on biomass gasification. Three types of gasification processes are compared, battelle gasification process, the fast internal circulating fluidized bed gasifier (FICFB) and the Blaue Turm gasification process. The processes are compared on the basis of exergetic efficiency and fond that FICFB gasification process is less efficient.

In 2008, Rashidi et al. [73] applied the exergy destruction method for exergy analysis to the hybrid molten carbonate fuel cell system. A parametric study is performed to examine the effect of varying operating pressure, temperature and current density on the performance of the system. Thermodynamic irreversibilities in each component of the system are determined. An overall energy efficiency, exergy efficiency, bottoming cycle energy efficiency and stack energy efficiency are calculated. The results demonstrate that increasing the stack pressure decreases the over potential losses and, therefore, increases the stack efficiency.

In 2008, Obara et al. [74] investigated the exergy flow and exergy efficiency of a proton-exchange-membrane (PEM) fuel cell was investigated using exergy destruction method. The exergetic efficiency of the system was calculated and the effect of change in the environment temperature on the exergetic efficiency was analyzed.

In 2008, Wang et al. [75] investigated the possibility of waste heat recovery in cement industry from the preheater exhaust and clinker cooler exhaust gases in cement plant. For this task, single flash steam cycle, dual-pressure steam cycle, organic rankine cycle and the kalina cycle are identified. The exergy analysis is examined, and a parameter optimization for each cogeneration system is achieved by means of genetic algorithm to reach the maximum exergy efficiency. The optimum performances for different cogeneration systems are compared under the same condition. The results show that the exergy losses in turbine, condenser, and heat recovery vapour generator are relatively large, and reducing the exergy losses of these components could improve the performance of the cogeneration system. Compared with other systems, the Kalina cycle could achieve the best performance in cement plant.

In 2008, Muangnoi et al. [76] analyzed the influence of the ambient temperature and humidity on the performance of a counter flow wet cooling tower according to the second law, exergy destruction method. The air is considered as the mixture of air and steam and proposed the method of calculation of its exergy. Exergy analysis then has been carried out for investigating the cooling tower performance with various inlet air conditions, relative humidity and dry bulb temperature, while the water side condition is kept constant. The similar result in terms of required dry air flow rate, exergy change of water and that of air, exergy destruction and second law efficiency were obtained for the various inlet air conditions.

In 2010, Saidur et al. [77] proposed the exergy analysis of industrial boiler. They showed that the total exergy destruction in the boiler is equal to the sum of exergy destruction in combustion zone and that in evaporation zone.

From the above review, it is seen that both the exergy analysis, viz. EGM and EDM are used to analyse various thermal systems. There are a number of studies carried out on vapour absorption refrigeration systems with LiBr/water and aqua ammonia as absorbent-refrigerant fluids. However, studies on AAVAR systems are relatively few, in spite of the fact that both are heat energy intensive systems and equally popular. Table 2.2 gives the summary of the various investigations on different system using exergy destruction method.

Table 2.2 Summary of Investigations on Various Thermal Systems Using EDM

System	Investigator	Year	Remark
Refrigeration & Air-conditioning Systems			
Vapour Absorption Refrigeration (VAR) System	Alvares et al.	1986	Analyzed the effect of generator temperature and evaporator pressure on exergetic COP and tried to optimize the aqua ammonia vapour absorption system
	Karakas et al.	1990	Performed exergetic analysis and found various losses in LiBr/ water and AAVAR system using solar energy as heat source
	Ataer et al.	1991	Studied the irreversibilities in the components of AAVAR system
	Aphornratana et al	1995	For single effect LiBr VAR system, studied the effect of various parameters on the performance of the system through exergy analysis.
	Ravikumar et al	1998	Checked the effect of generator temperature for double effect Li Br vapour absorption system
	Kilic et al	2004	Analyzed the effect of main system temperatures on the performance parameters of the system, irreversibilities in the thermal process and non-dimensional exergy loss of each component of LiBr VAR system.
	Sencan et al	2005	Evaluated the exergy loss, enthalpy, entropy, temperature, mass flow rate and heat rate in each component of the LiBr/water VAR system.
	Morosuk et al.	2008	Identified endogenous and exogenous parts of exergy destruction in absorption system .Estimated the exergy destruction in a component caused by the component itself on one hand and by the remaining components on the other hand
	Gomri et al.	2008	Analyzed the effect of effect of temperature of LPG and HPG on the performance of LiBr/water VAR system.
	Gomri et al.	2009	Compared the COP of single effect and double effect LiBr/water VAR system.
Vapour compression refrigeration system	Mastrullo et al.	1987	Evaluated, for multi stage VCR system, plant exergetic efficiencies, equipment irreversibility, and their sensitivity to main system parameters.

	Kumar et al.	1988	Compared the exergetic performance of VCR, using R11 and R12 as refrigerants
	Lohlein et al.	1993	Checked variety of arrangements of component in low temperature refrigerators through exergy analysis.
	Aprea et al.	2002	Compared the performance of the system with refrigerant R22 and R407C.
	Srinivasan at el	2003	Analyzed the effect of gas cooler pressure on the exergetic efficiency of the system.
	Fartaj at el	2004	Analyzed transcritical CO_2 refrigeration cycle and showed that the compressor and the gas cooler exhibit the largest non-idealities within the system.
	Dopazo et al.	2008	Analyzed a cascade refrigeration system with CO_2 and NH_3 as working fluids in the low and high temperature stages, respectively
	Mafi et al.	2009	Analysed cascade refrigeration and shows that the minimum work depends only on the properties of incoming and outgoing process streams cooled or heated with refrigeration system and the ambient temperature.
Air-Conditioning Systems			
Air conditioning system	Bilgen et al.	2002	Compared the performance based on first law and second law.
	Wei et al.	2009	Analyzed the Variable Air Volume type Air Conditioning system.
Combined Refrigeration and Other Thermal Systems			
Cogen Plant	Vidal et al	2006	For power/refrigeration plant, showed that the solar collectors or waste heat can be the best heat sources to operate the cycle.
	Dai et al.	2008	For combined, power and refrigeration cycle, which combines the rankine cycle and the ejector refrigeration cycle, performed exergy analysis
	Khaliq	2008	Analyzed trigeneration system generating electricity, process heat and cooling effect.
	Kelly et al.	2009	Applied the concept of exergy splitting to VCR system and gas power plant suggested by Morosuk
Other Thermal Systems			
Power generation system	Nag et al.	1995	Evaluated the effects of pressure ratio and peak cycle temperature ratio of the gas

			cycle and the lower saturation pressure of the steam cycle on the overall performance of the combined plant.
	Hamed et al.	2006	Calculated the exergy destruction in each component of power/water cogen plant and calculated the appropriate cost of it.
	Abusoglu et al.	2008	Calculated the exergetic efficiency for diesel engine powered cogeneration systems generating electricity and steam.
	Rakopoulos	2008	Developed the zero-dimensional, multi-zone, thermodynamic combustion model based on second law analysis.
	Som et al	2008	compared the combustion of solid, liquid and gaseous fuel using both methods
	Kanoglu et	2008	Analyzed the effect of turbine inlet pressure and condenser pressure, on the exergetic performance of binary geothermal power plant.
	Aljundi	2009	Analyzed steam turbine based power plant.
	Kamate et al.	2009	Identified the optimal steam inlet condition to steam turbine exergetic point of view.
Solar Energy Based Systems			
Solar heating system	Gunerhan et al.	2007	Investigated the effect of various parameters on the performance of the system.
	Celma et al.	2009	Analyzed solar drying process and estimated the exergy losses.
Solar trigeneration system	Zhai et al.	2008	For solar heating, chilling and power generation system, found the exergy loss in various components.
Solar power plant	Gupta et al.	2010	Analyzed direct steam generation solar power planr
	Baghernejad et al.	2010	Identified exergy destruction in the various components of solar combine cycle system
Solar still	Torchia-Nunez et al.	2008	Steady-state and transient theoretical exergy analysis of a solar still, focused on the exergy destruction in the components
Solar collector	chow et al.	2009	Analyzed photovoltaic thermal collector with and without glass cover.
	Farahat et al	2009	optimized flat plate solar collector.
Miscellaneous Thermal Systems			

Heat exchanger	Yilmaz et al.	2001	Compared EGM and EDM method
Gasifier	Ptasinski et al.	2007	Compared different types of bio-fuels for their gasification efficiency
	Toonssen et al.	2008	
Fuel cell	Rashidi et al.	2008	For the hybrid molten carbonate fuel cell, examined the effect of varying operating pressure, temperature and current density on the performance of the system.
	Obara et al.	2008	Investigated the exergy flow and exergy efficiency of a proton-exchange-membrane fuel cell.
Cooling tower	Muangnoi et al.	2008	Analyzed the influence of ambient temperature and humidity on the performance of the system.
Boiler	Saidur et al.	2010	showed that the total exergy destruction in the boiler is equal to the sum of exergy destruction in combustion zone and that in evaporation zone

2.1.3 Comparison between EGM and EDM

Table 2.3 gives comparison of EGM and EDM. It is seen that both the methods are useful in predicting the quality and quantity of energy utilized in thermal systems. However, it is reported that EGM poses difficulties in combining both exergy and cost analysis. Exergoeconomic analysis thus, needs the exergy balance and exergy destruction method (EDM) along with a suitable cost analysis.

Table 2.3 Comparison of the Exergy Analysis Methods

Method	Overview of Method	Remark
EGM	• Individual components are identified. • For each component, entropy associated with inlet and outlet flow is calculated. • Entropy change is multiplied with environment temperature and exergy destruction is calculated. • Loss in each components are found	• All components can be analyzed. • Only destruction can be found but fuel and product cannot be identified. • Difficult to combine with Exergoeconomic analysis
EDM	• For each component, exergy flow at inlet and outlet is calculated. • Difference in exergy at inlet and outlet is considered as fuel or product as per the application. • Unaccounted exergy is considered as exergy destruction.	• Components like throttle valve cannot be analyzed. • For some components, difficult to identify fuel and product. More than one component to be combined as a single component. • Easy to combine with exergoeconomic analysis.

2.2 Exergoeconomic Analysis

The exergy analysis yields the desired information for a complete evaluation of the design and performance of an energy system from the thermodynamic viewpoint. However, one still needs to know how much the exergy destruction in a plant component costs the plant operator. Knowledge of this cost is very useful in improving ('optimizing') the cost effectiveness of the plant. Exergy not only is an objective measure of the thermodynamic value of an energy carrier but also is closely related to the economic value of the energy carrier, because users pay only for the useful part of energy. Exergy costing is based on the notion that exergy is the only rational basis for assigning costs to energy carriers and to 'energy waste' (exergy destruction and exergy losses, respectively). Thus, exergy costing uses costs per exergy unit. Exergoeconomics is based on exergy costing and is usually applied at the plant-component level. This section will deal with the exergoeconomic analysis carried out by various investigators.

One of the ways to apply exergy costing is to charge throughout the plant for exergy destruction and exergy losses at a uniform cost per exergy unit equal to the average cost per exergy unit of the fuel of the total plant. This approach, however, does not consider that the importance of exergy destruction and exergy loss, from both the thermodynamic and economic viewpoints, depends on the relative position of the sub system where the exergy destruction occurs within the total plant. For example, one MW of exergy destruction rate in the low-pressure steam turbine affects the cost of electricity more than an exergy destruction rate of one MW in the boiler of a steam power plant. Therefore, more sophisticated approaches to exergy costing are required.

In 1981, Shiran et al. [78] tried to apply thermodynamic analysis based on first law and economic analysis in combination to AAVAR system and tried to optimize the system thermoeconomically.

In 1982, London [79] tried to relate exergy and economy using the case of steam power plant. Starting with recognition of the individual internal and relevant external irreversibility thermodynamic arguments are used to formulate both entropy and energy measures in terms of operating conditions. The energy measures, lead to economic pricing relating to system energy expenditure and sometimes system energy rating penalties. The analysis loop is closed by considerations relating to the reduction of the individual irreversibility in terms of trade-off factor. The available energy or exergy analysis provides an answer to the overall costs of the collective internal irreversibility.

In 1989, Duarte et al. [80] tried to analyze optimal working conditions for an absorber heat transfer analysis of the LiBr/water theoretical cycle. They showed that the optimal circulation ratio will give the maximum profit for a given investment. The cost of each piece of equipment is an increasing function of its heat exchange surface area, which is proportional to the heat transfer. The surface area depends also upon the design characteristics of the equipment, but the product (UA) is only a function of LMTD and heat transfer rate. A relation between the temperature uplift and heat transfer driving force Δt^h (temperature change for hot fluid) is suggested by them. When Δt^h diminishes, the circulation ratio increases but, the LMTD diminishes, and therefore the parameter (UA) increases which would increase proportionally the equipment cost. It can therefore be deduced that the optimal value of Δt^h must be calculated from a careful economical evaluation.

In 1996, Saghiruddin et al. [81] applied the energy costing to VAR system and using three types of working fluid and three type of energy source. The costs of the sources of energy estimated for the solar collector areas and volume flow rates of biogas and LPG, for a typical operating condition in the absorption cycles with respect to generator temperature by plotting the variation of cost against the generator temperature and found minimum corresponding cost for optimum generator temperature iteratively.

In 2003, Zhang et al. [82] carried out thermoeconomic optimization of small size central air conditioner. They carried out exergy analysis on the basis of entropy generation minimization and defined cost function to be minimized.

In 1998, Kim et al. [83], proposed another method for exergoeconomic analysis of thermal system with the application to power plant. They derived general cost balance equation which can be applied to any component of the system. The exergy of the material stream decomposed in to thermal mechanical and chemical exergy flows and an entropy production flow. A unit exergy cost is assigned to them. Then the set of equations for the unit cost of various exergies is obtained by applying the cost balance to each component of the system and to each junction. The monetary evaluations of various exergy cost, as well as production cost of electricity are obtained by solving the set of equations. The lost cost of each component also can be obtained.

In 2004, Kwaka et al. [84] carried out Exergetic and thermoeconomic analysis of a phosphoric acid fuel cell plant. The above publications are the individual efforts and not following any systematic methodology. In the following section, few standard exergoeconomic methods are explained. In each method, first the refrigeration and air conditioning system under analysis is discussed. Subsequently the other systems are discussed.

2.2.1. Thermoeconomic Evaluation and Optimization (TEO) Method

In 1985, Tsatsaronis et al. [3] proposed thermoeconomic optimization of thermal system. After calculating mass, energy and exergy balance for total system, levelized investment and operating cost of each component of coal fired power plant (economic analysis) is carried out. Then the cost of the exergy unit of each process flow stream is calculated. Marginal exergy unit cost for fuel and product of each plant component is calculated. Then the cost of the exergy losses in each plant component is calculated.

Refrigeration and Air conditioning system

In 1997, Cammarata et al. [85] used the same approach to optimize the air conditioning system. The thermodynamic model is stated according to recent formulations of exergy for moist air streams, while the economic model is based on cost balance equations and real cost data for mechanical equipment. The objective function to minimize includes decision variables such as fresh to total air rate, coefficient of performance for the chiller, inlet temperature of water for the cooling and the heating coils, and temperature difference of the same streams.

In 2004, Morosuk et al. [86] tried to combine TEO method with pinch technology and applied to low temperature refrigeration system (Cryogenic system) generating temperature between -100 °C to -150 °C.

In 2005, Leo et al. [87] applied TEO method to commercial aircraft environmental control system and the cost per unit of exergy of the conditioning stream entering the cabin has been obtained for a range of the aircraft engine bleed pressure values. A minimum cost has been found at a pressure close to the nominal bleed pressure.

Using this approach, in 2003, Misra et al. [88] carried out exergoeconomic analysis and optimized single effect LiBr/water VAR system. In 2005, they extended the analysis for double-effect LiBr/water VAR system [89] and in 2006, AAVAR machine [90].

Power generating system

In 1993, Tsatsaronis [3] suggested the improved method for exergy costing in which a average cost (monetary) value is assigned to each material and energy stream in the energy-conversion system (process) being considered. This value represents the total cost required to produce the stream. He presented a case study of an exergoeconomic analysis of power plant.

In 2002, Tsatsaronis et al. [92], identified avoidable and unavoidable exergy destruction and associated cost and applied to cogeneration system. In 2006, Cziesla et al. [93] continued this work and applied to an externally fired combined cycle power plant. For each plant component, avoidable and unavoidable exergy destructions and investment costs are calculated.

In 2007, Notario et al. [94] suggested that the thermal component of exergy ϕ^{TM} should be divided in to two parts. $\phi^{TM} = \phi^{tb} + \phi^{ta}$ as shown in Fig. 2.1. Where ϕ^{tb} represents the work produced (or required) in the isentropic expansion (or compression) process at ambient pressure, zero velocity and zero potential energy level. This part of the thermo mechanical exergy is known as the thermo baric component, and its energetic quality is comparable to that of work and ϕ^{ta} represents an exclusively thermal-type exergetic component at the ambient pressure p_a called thermo ambient component. To reversibly convert this into work is a highly complex task. The economic values of these two components are clearly different, and the thermo baric component has a higher value than the thermo ambient component in the case of thermal engines. The economic evaluation of both thermo mechanical exergy components is carried out for the case of combine cycle power plant.

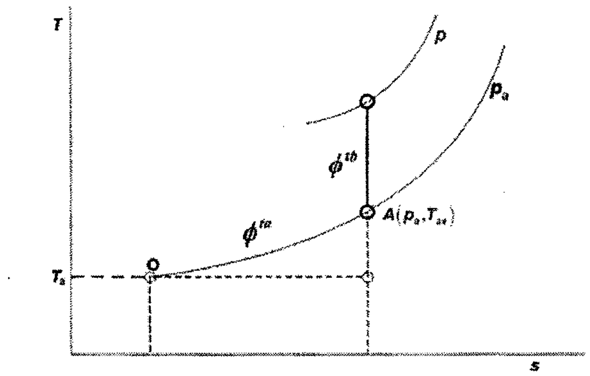

Fig. 2.1: Division of Thermo Mechanical Exergy into Thermo Baric and Thermo Ambient Components [93]

In 2009, Abusoglu et al [95, 96] used the SPECO method to find specific exergy cost to analyze diesel engine powered cogeneration plant. After calculating specific exergy cost, a detailed exergoeconomic analysis is carried out using TEO method. It is observed that the specific unit exergetic cost of the power produced by the plant is 10.3 $/GJ.

Power plant in combination with other system

In 2006, Tsatsaronis et al. [97] carried out exergoeconomic optimization of a novel zero-emission process generating hydrogen and electric power. In 2009, Modesto et al. [98] used TEO method for exergoeconomic optimization of the power generation system using blast furnace and coke oven gas in a steel mill.

In 2010, Cortes et al. [99] tried to combine exergoeconomic methodology with pinch technology and applied to a cogeneration power plant with pulp and paper mill. They proposed improvements to the plant, through the modification of the operating conditions and the implementation of new equipment. The location of the new equipment was determined using pinch technology and the exergoeconomic optimization was carried out through TEO method.

Gasifier

Subsequently Lazzaretto et al. [100] proposed this methodology systematically considering the case of gasifier, by taking a systematic record of all exergy additions to and removals from all the exergy streams of the system and the costs are calculated by applying basic principles from business administration. Thus, a direct link between the definitions of fuel and product for a component and the corresponding costing equations is established. In particular, the paper shows how to obtain detailed definitions of exergetic efficiencies using separate forms of exergy (thermal, mechanical and chemical) and how, according to these definitions, to conduct an evaluation of costs associated with all the exergy streams entering and leaving a system component. For this case, the cost equations are presented in a general matrix form.

Boiler

In 2010, Ozdemir et al. [101] applies TEO method to a fluidized-bed coal combustor (FBCC) of steam power plant. He considered ventilation fan, FBCC, HRSG, cyclone, economizer, aspiration fan, pump and chimney as sub systems and calculated the exergy destruction in each part and cost of steam generated.

2.2.2 Theory of Exergetic Cost

In 1993, Lozano et al. [102] proposed theory of exergetic cost. It is based on the concept of; a higher irreversibility in a sub system always implies higher consumption of resources of the plant if the products remain constant. It is essential to link the variation in the local irreversibility to the increase of resources consumed. The plant will be defined as a set of sub systems or units linked to each other and to the environment by another set of matter, heat, and work flows. The relationship between the flows and sub systems is set up through the incidence matrix. After developing the thermodynamic and cost model, the exergetic and thermoeconomic cost balance equations are formulated with the help of fuel product definition.

Refrigeration and Air conditioning system

In the year 1997, Accadia [103] analyzed the vapour compression refrigeration plant using exergetic cost theory. In 2002, Misra et al. [104] applied theory of exergetic cost to the LiBr/water VAR system.

Power generation system

In 2006, Modesto et al. [105] applied same method to the power plant, generating power from the waste heat of a steel mill plant. The system was assessed by means of two thermoeconomic methodologies, Theory of Exergetic Cost and Thermoeconomic Functional Analysis; exergetic and monetary costs of power production were calculated and compared to the respective values of the current system.

In 2007, Aguilar [106] analyzed steam turbine using exergetic cost theory. In the first part, the relationship between entropy and enthalpy modifications due to stage malfunctions are developed to evaluate their economic impact, based on the cost of irreversibility in a system. The second part of the work, they determined and evaluated the degree of entropy generation and power loss in a steam turbine stage (nozzle-bucket), under the detection of specific malfunctions such as roughness, seal and leak clearances, erosion, and sedimentation. Then the computation of exergy-cost and economic-cost of local products and fuels in steam turbines is carried out.

Engine

In 2006, Sala et al. [107] analyzed container housed engine using theory of exergetic cost and optimized the system to calculate the minimum cost of the electricity and useful heat energy produced by the engine. As an output, identified the exergy losses and areas of improvement.

2.2.3 Engineering Functional Analysis (EFA)

Refrigeration and Air conditioning system

In 1986, Wall [108], analyzed heat pump, used autonomous method, also known as EFA method. His decision variables are the efficiencies of the compressor, the condenser, the evaporator, and the electric motor. The system is completely defined apart from the decision variables, each set of which determines a state of the system. The exergy flows and exergy losses are also determined for each component. The objective is to minimize the cost for a given amount of produced heat. The cost includes both the operating (electricity) cost and the capital cost. The operating cost increases if the investments decrease and vice versa. The income from the product (heat) and a given required value of the profit sets an upper limit for the total cost of the system. In 2004, Al-Otaibi et al. [109], followed similar procedure to optimize the vapour compression refrigeration system.

Power generation system

In 2003, Rosen M A et al. [110] examine the relations between thermodynamic losses and capital costs for devices in several modern coal-fired power plants, and suggest possible generalizations in the relation between thermodynamic losses and capital costs. They compared the performance of power plants operating on various fuels.

2.2.4 Thermoeconomic Functional analysis

In 1987, Frangopoulos [111] suggested Thermoeconomic Functional analysis (TFA), is a method for optimal design or improvement of complex thermal systems. Each unit has a particular quantified function (purpose or product). The distribution of functions establishes inter-relations between units or between the system and the environment and leads to a functional diagram of the system. The optimization minimizes the total cost of owning and operating the system, subject to constraints revealed by the functional diagram and analysis.

Power generation system

In 1996, Frangopoulos et al. [112] applied thermoeconomic functional analysis to the cogeneration system of the refinery and optimized the system.

In 1990, a group of concerned specialists in the field (**C.** Frangopoulos, **G.** Tsatsaronis, **A.** Valero, and **M.** von Spakovsky) [113 to 117] decided to compare their methodologies by solving a predefined and simple problem of optimization: the CGAM problem, which was named after the first initials of the participating investigators. The objective of the CGAM problem is to show how the methodologies are applied, what concepts are used and what numbers are obtained in a simple and specific problem. In the final analysis, the aim of the CGAM problem is the unification of thermoeconomic methodologies. This comparison is not a competition among methodologies. Each methodology has specific fields of applications for which it provides proven and efficient solutions.

2.2.5 Structural Method

As cited by Kotas [118] the structural method was developed by Beyer and is proved as one of the best method for system optimization. This method is using the unitary costs of exergy loses. Structural coefficients are used in the study of the system structure, for the optimization of plant components and product pricing in multi-product plants.

Refrigeration and Air conditioning system

In 2004, Selbas [119] optimized vapour compression refrigeration cycle with subcooling and superheating. The final equation of irreversibility was applied to condenser, evaporator, subcooler and super heater. On the common plot, variation of irreversibility v/s area and cost v/s area was plotted. The point of intersection is the optimum area of the heat exchanger. In 2004, Accadia et al. [120] optimized condenser in a vapour compression heat pump using the same method.

In 2005, Misra et al [121] applied the structural theory to LiBr/water absorption chiller. Their analysis reveals that the capital cost of the optimum configuration is increased by about 33.3% from the base case; however, the additional cost is well compensated by reduced fuel cost. This is possible because of reduction of plant irreversibilities by about 47.2%. In 2006, Kizilkan et al. [122] used this technique for thermoeconomic optimization of a LiBr/water VAR system.

Power generation system

In 1999, Erlach et al. [123] tried to apply Last in First out (LIFO) approach to the structural method in application with combined cycle power plant. The LIFO approach is a cost accounting method used to calculate the cost of the fuel and product of the components, which are defined as the resources consumed to generate these fuels and products, respectively. The costs are calculated from a linear equation system consisting of the cost balances of the components, which can be obtained from the physical structure of the system and some auxiliary equations required for the components that have more than one outlet flow. The auxiliary equations express the fuel and product distribution given by the thermoeconomic model.

In 2002, Torres et al. [124, 125] improved the structural theory by computing the additional fuel consumption as the sum of both the irreversibilities and the malfunction costs of the gas turbine power plant components. It will be able to quantify the effect of a component malfunction in the other components of the plant. The key of the proposed method is the construction of the malfunction/dysfunction table which contains the information related with the plant inefficiencies and their effects on each component and on the whole plant.

In 2006, Zhang et al. [126] applied a cost analysis method based on structural method to a pulverized coal fired power plant. An exergy analysis is performed to calculate the exergy and negentropy of the flows. Then, a thermoeconomic model of the plant is defined based on the functionality of each component using the fuel–product definition. The distribution of the resources throughout the plant and the costs of all flows in the production structure can be calculated by solving a set of equations including the thermoeconomic model of the plant. Three thermoeconomic variables are defined for improving the exergy cost equations in the structural theory of thermoeconomics.

In 2006, Valero et al. [127] explained the structural theory in detail with the example of gas power plant. They explained the difference in average and marginal cost, Building of productive structure, thermoeconomic model and cost estimation in first part. In Part II [128] they developed the mathematical formulations of three applications of the thermoeconomic analysis methodology described in Part I: the operation diagnosis study, including new concepts that helps to separate different contributions to those inefficiencies; the local optimization process in case of special conditions for the whole plant, and the benefit maximization (a direct application of the exergy costs accounting analysis). The operation diagnosis, which is the most complex and sophisticated application, is presented with the help of an example: the co-generation plant, as it was described in Part-I.

In 2006, Zhang et al. [129] presented a progressive separation procedure of the induced effects for power plant system diagnosis based on structural theory and symbolic thermoeconomics. The malfunction/dysfunction analysis and the fuel impact analysis of the structural theory as well as an improved induced malfunction evaluation method, which is composed of a progressive separation procedure, are applied to a coal fired power plant. First, the dysfunctions induced by the malfunctions are separated by the malfunction/dysfunction analysis from the irreversibility increases in the components. The effects of the malfunctions on each component and the whole plant are also evaluated by using the fuel impact analysis. Then, the induced malfunctions generated by the inefficiencies in the other components are separated from the remaining irreversibility increases (i.e. malfunctions) by using the induced malfunction evaluation method proposed by them. This method enables evaluation of the induced malfunctions in thermoeconomic diagnosis applications. After separating the induced effects, the real anomalies can be quantified and localized.

Power generation system in combination with other system

In 2008, Deng et al. [130] used structural theory for the exergoeconomic analysis of gas-fired micro-trigeneration system, which uses a small-scale generator set driven by a gas engine and small-scale adsorption chillier, generating electricity, cooling and heating effect. A comparison between the method of conventional exergy analysis and exergy cost analysis is presented. The result reflects that the structural theory is a powerful and effective tool for performance evaluation of complex system, and also proves that the micro-trigeneration system is efficient in utilizing the low-grade waste heat.

Heat exchanger

In 2002, Accadia et al. [131] determined the optimal configuration of a heat exchanger with a two-phase refrigerant using exergoeconomics by structural method. In their paper, the irreversibility due to heat transfer across the stream-to-stream temperature-difference and to frictional pressure-drops is calculated as a function of two design variables: the inner-tube's diameter and the saturation temperature of the refrigerant, on which the heat-exchange area directly depends. Then, a cost function is introduced, defined as the sum of two contributions: the amortization cost of the condenser under study and the operating cost of the conventional electric-driven heat-pump in which this component will have to work. The latter contribution is directly related to the overall exergy destruction rate in the plant, whereas the amortization cost mainly depends on the heat-exchange area. So, design optimization of the device can be performed by minimizing this cost function with respect to the selected design variables. The Coefficient of Structural Bond is used in the optimization to relate the local irreversibility in the condenser to the overall exergy destruction rate in the heat-pump plant. For a commercial heat-exchanger, the design improvements needed to obtain a cost-optimal configuration are investigated. The results show that significant improvements can be obtained with respect to devices based on conventional values of the design parameters.

2.2.6 Evolutionary programming (EP)

Evolutionary programming, originally conceived by Fogel [132] in 1960, is a stochastic optimization strategy similar to genetic algorithms (GA), from which it differs in its emphasizing the behavioral linkage between parents and their offspring, rather than seeking to emulate specific genetic operators as observed in nature. EP is a powerful method of optimization when other techniques such as gradient descent or direct analytical discovery are not possible. For EP, a fitness landscape can be characterized in terms of variables, and that there is an optimum solution (or multiple such optima) in terms of those variables. In 2007, Sahoo [132] applied this methodology to cogeneration plant and in the same year Koch et al. [133] used the same method for Optimization of combined cycle power plants.

In Europe, this methodology is known as Genetic Algorithm. In 1998, Cammarata et al. [134] formulated the objective function, the sum of the capital, and the operational and maintenance costs, of a district heating network using exergoeconomic concepts and minimized the objective function using genetic algorithm (GA) and found the suitability of this concept. In 2002, Toffolo et al. [135] used the multi-objective evolutionary algorithm for simultaneous exergetic and economic optimization of the CGAM problem. In 2008, Caputo et al. [136] carried out economic optimization of heat exchanger using genetic algorithm and showed that significant cost reductions are feasible with respect to traditionally designed exchangers.

2.2.7 EEA method

In 2001, Sciubba [137] realized that exergy analysis, though completely satisfactory from a thermodynamic point of view, has always been regarded as unable to determine real design optima, and therefore its use has been associated with customary monetary cost-analysis. He suggested the concept of Extended Exergy Accounting (EEA). He defined the term invested exergy. It is equal to the sum of the 'non-energetic' externalities (Labor and Capital) used in the construction and operation of the plant in which the product is generated. For any product, it is then conceivable to define an 'extended exergy' as the sum of the physical exergy and the proper portion of the invested exergy that can be assigned to the stream under consideration. Using this approach, he analyzed the gas turbine based cogeneration system.

In 2007, Verda et al. [138] proposed procedure, based on this method with the aim of locating and quantifying malfunctions in the system. The value of malfunction can be correlated with economic value.

2.2.8 Exergetic Production Cost method (EPC)

In 2003, Silveira et al. [139,140] proposed method, and applied to power plant. The developed technique has as objective the minimum (optimal) total operating costs of the cogeneration plant (EPC), assuming a fixed rate of electricity production and process steam. The operating cost of each component of the plant is calculated. Taking the example of pump, the cost of the outflow stream is the sum of inflow stream cost, pump work cost and investment and maintenance cost. Similarly the operation cost for other components are found. The objective function to be minimized is the EPC. The operating parameters selected to be optimized are temperature and pressure leaving the boiler for systems with steam turbine, and pressure ratio, flow rate and temperature of exhaust gases for systems with gas turbine. Those parameters are selected because of their influence over the power generated and the purchase costs of the components. The EPC equation is formulated as a function of these operating parameters. The function minimization is done with the help of computer program. Using similar method, in 2003, Camargo et al. [141] carried out thermoeconomic analysis of an evaporative desiccant air conditioning system.

2.2.9 Graphical Method

In 2002, Can et al. [142] suggested that the previous methodologies are tedious and proposed graphical solution considering the case of condenser type of heat exchanger. In this method, first a diagram for the investment and exergy loss expenses is drawn and then the Optimum Operation Point is determined by intersection of the investment line and operation line.

2.2.10 Input-Output Method

In the year 1994, Alvarado et al. [143], presented and called input-output exergoeconomic optimization, applied to the cogeneration plant (the CGAM problem). The selection of sub systems or components to be optimized is dictated by two parameters: the exergetic efficiency and the elasticity, the latter measuring the variation of global system efficiency with efficiency change of the sub system, both evaluated for the given operational conditions. The proposed method gives results that agree quite closely with those of the authors of the CGAM problem.

In 2009, Abusoglu et al. [144] discussed various thermoeconomic methodologies considering the case of CGAM problem and exergoeconomic analysis and optimization of combined heat and power production are presented. In the same year, Lazzaretto [145] presented a comparison between thermoeconomic and energy analyses (TA) algebra using the case of cogeneration system. In energy analysis, he included all human and natural inputs, energy, material, human labour and information and the combination of all these is called as emergy and application of it is called emergy analysis (EMA). He concluded that the TA is based on the idea that the monetary cost and exergy cost are conserved at system (or component) level. Unlike TA, the EMA attention is not on system (or components) but on system (or component) products. The idea is to take a record of all the energy that was previously required to generate each of the system (or component) products, separately.

In 2010, Kim [146] presented a new thermoeconomic methodology for energy systems, the wonergy method. In this methodology, various energies, including enthalpy and exergy, can be integrated with ''wonergy'', a portmanteau of ''worth'' and ''energy'' and is defined as an energy that can equally evaluate the worth of each product, and worth is not an absolute number but a relative concept. He applied this method to CGAM problem and compared with various conventional methodologies.

In 2010, Miguel et al. [147] carried out Cost optimization of the design of combined heat, cooling and power (CHCP) systems under legal constraints. An optimization model is developed, using mixed integer linear programming (MILP), to determine the preliminary design of CHCP systems with thermal storage. The objective function to be minimized is the total annual cost. Taking into account the legal constraints imposed on cogeneration systems in Spain, the optimization model is applied to design a system

The above review of literature shows that the exergoeconomic optimization is having the major field of application in power plant as they are having huge capital investment. Minor variation in the working parameter also brings drastic change capital investment and operating cost. For other thermal systems, especially refrigeration systems, limited applications are observed. Due to ozone layer depletion and global worming problem, the VAR systems are getting more and more popularity. But VAR systems are heat intensive and facing a problem of huge capital investment. Just like power plant, the optimization of VAR system by variation in working parameters can bring major reduction in investment and operating cost. The major publications are in the field of LiBr/water VAR system but very few for AAVAR system. Moreover all publications are found with independent boiler as heat source. The literature review of publications related with gas and steam turbine power plant reveals that the optimization of gas turbine power plant with HRSG can bring appreciable reduction in the cost of electricity as well the cost of steam generation [114]. Similarly, the exergoeconomic optimization of steam turbine power plant with regeneration [139,140] can bring reduction in the cost of electricity and shows that the cost of steam tapped from steam turbine will be less than the cost of steam generated in the independent boiler.

2.3 Problem Formulation

From the review of various investigations on exergoeconomic analyses on thermal systems, it can be seen that, many optimization methods are in use. The summary of all the methods is given in Table 2.4. All these methods are independent and used as per the application. It is further observed that almost all of them are stand-alone methods developed by the respective investigators and the complete details are not readily available from the published literature for the user to adapt them with ease. Thermoeconomic Evaluation and Optimization Method suggested by Tsatsaronis [1], however, is found to be the most user friendly method.

As the method is available in open literature, it is decided to analyse AAVAR System using this method. From the reported investigations of Misra et al. [90], it is observed that the components like throttling valve and expansion valve have to be excluded from the analysis when TEO method is employed. However, as the exergy destruction in these components cannot be avoided and must be included in the overall system analysis, it is necessary to find suitable scheme for the purpose. Due to the limitation of the exergy destruction method that Misra et al. have adopted in their analysis, the actual performance of condenser and evaporator cannot be judged. Therefore, the present proposed research study will include Entropy Generation

Minimization Method in Thermoeconomic Evaluation and Optimization (TEO) method so as to take care of the limitations. It is expected that the proposed study will be more general in nature.

TEO method suitably modified using Entropy Generation Minimization (EGM) method is proposed to be employed to optimize the existing AAVAR system with independent boiler as a heat source in the fertilizer industry for minimum cooling cost to be achieved. There are two different heat sources, viz., steam generated at HRSG of gas power plant and tapped steam from steam power plant, available as alternative energy options in the fertilizer industry which can be incorporated to AAVAR system. It is proposed that these options be examined using the optimization method developed. Then, the cooling costs of AAVAR system with different heat source options be compared and optimum cost be decided.

2.4 Objectives of the Research

The following are the objectives for the present research work:

- To develop the user friendly method for exergy analysis of thermal system systems by combining the EDM method and EGM method of exergy analysis.
- To carryout exergy analysis of AAVAR system, Gas Turbine Power Plant and Steam Turbine Power Plant and to identify losses in the various components of these systems.
- To carryout exergoeconomic optimization of AAVAR system with independent boiler as heat source and to decide optimum cost for cooling generated at evaporator.
- To identify alternative options as heat source for AAVAR system other than independent boiler.
- To carryout exergoeconomic optimization of AAVAR system and GT-HRSG jointly using steam generated at HRSG as heat source.
- To carryout exergoeconomic optimization of AAVAR system and steam turbine power plant jointly using tapped steam from steam turbine as heat source.
- To identify most economical heat source for AAVAR system from the options available in the fertilizer industry.

Table 2.4: Summary of Investigations on Exergoeconomic Optimization Methods

System	Type of system	Investigator	Year	Exergoeconomic method used	remark
Refrigeration and Air conditioning systems					
Absorption Refrigeration System	LiBr-Water	Misra R D et al. (India)	2002	Exergetic Cost Theory	
	LiBr-Water	Misra R D et al. (India)	2003	TEO	
	LiBr-Water Double effect	Misra R D et al. (India)	2005	TEO	
	LiBr-Water	Misra R D et al. (India)	2005	Structural Method	
	Ammonia Water	Misra R D et al. (India)	2006	TEO	
	LiBr-Water	Kizilkan O et al. (Turkey)	2007	Structural Method	
Vapour Compression Refrigeration system		Accadia M D et al. (Italy)	1998	Exergetic Cost Theory	
	R-134a as refrigerant	Otaibi D A et al. (Saudi Arabia)	2004	Engineering Functional Analysis	
		Selbas R et al. (Turkey)	2004	Structural Method	Subcooling and Superheating are considered
Air Conditioning System	Heat Pump	Wall G (Sweden)	1985	Engineering Functional Analysis	
	Re circulation type	Cammarata G et al.	1997	TEO	Average cost

		(Italy)			approach
	Central A/C Small size	Zhang G Q et al. (China)	2003	Engineering Functional Analysis	
	Desiccant A/C	Camargo J R et al. (Brazil)	2003	Exergetic Production cost method	
Power generating systems					
Power Plant	Steam power Plant	Tsatsaronis G Winhold M (Germany)	1984	TEO	LIFO approach
	Steam power plant	Tsatsaronis G (Germany)	1993	TEO	Average cost approach
	Steam power plant	Lozano M A et al. (Spain)	1993	Exergetic Cost Theory	
	Combine Cycle Power Plant	Notario P P Leo T J (Spain)	2005	Converted economy in to equivalent exergy	Assigned different cost to thermal and mechanical exergy
	Combine Cycle Power Plant	Cziesla F Tsatsaronis G (Germany)	2006	TEO	Average cost approach
Power plant in combination with other system					
Cogeneration Power plant	Heat and power generation	Silveira J L at el. (Brazil)	2003	Exergetic Production cost method	
	Electricity + Hydrogen	Tsatsaronis G Kapanke K (Germany)	2006	TEO	Average cost approach

	Power/water cogeneration plant	Hamed O A (Saudi Arabia)	2006	Structural Method	
	Cogeneration plant	Modesto M et al. (Brazil)	2006	Exergetic Cost Theory Thermoeconomic functional Analysis	Gas from blast furnace and coke oven gas Compared ECT and TFA
	Cogeneration plant	Valero A et al. (Spain)	2006	Structural Method	Compared average and Marginal cost
	Cogeneration Plant	Sahoo P K (India)	2008	Evolutionary Programming	
Miscellaneous system					
Steam Turbine		Aguilar A Z et al. (Mexico)	2007	Exergetic Cost Theory	Exergy cost of turbine steam emission is found
Engine	Container housed type	Sala J M et al. (Spain)	2006	Exergetic Cost Theory	
Heat Exchanger	Counter flow Parallel flow Single fluid (Ratio of heat capacity rate = 0)	Soylemez M S (Turkey)	2000	Saving function is developed in terms of exergy and area And optimized the system	Based on thermodynamics fundamentals
	Tube in Tube type (Two Phase Refrigerant)	Accadia M D et al. (Italy)	2002	Structural Method	

Table 2.5 Comparison of Various Exergoeconomic Optimization Methods

Sr. No.	Method	Overview of the Method	Remark
1	Thermoeconomic Evaluation and Optimization Method	• Based on local optimization of sub systems • Follow iterative procedure • Consider actual component level penalty function.	• Heat dissipative devices like throttle valve can not be analyzed. • No computer programming is required • User friendly
2	Exergetic Cost Theory	• Cost are calculated for the system as a whole	• Using the negentropy concept, heat dissipative devices can be analyzed.
3	Thermoeconomic Functional Analysis	• Exergy and negentropy flows are determined • Functional diagram is prepared • Standard cost functions used for all components • Cost flows are solved using Lagarangian multiplier • Objective function, to be minimized, is formulated	• Cost functions for the components like throttle valve are not defined • Preparation of functional diagram involves individual judgment • Solution of Lagarangian multiplier needs high level of computer skill • Decision of constrains & decision variable depends on individual
4	Autonomous Method	• Objective function, to be minimized, is defined • Cost model of each equipment is used • system product, input, same at branch and junctions are determined • secondary product handled by branch • Junction represents mixing of two fluid • Functional diagram is prepared • Using the internal economy, Lagarangian associated with the objective function is	• similar to TFA • judgment of branch and junction involve individual decision • functional diagram is complicated • solution of Lagrange is difficult

		formulated • Other algorithms are also possible for solution	
5	Structural Method	• For the plant component, change in irreversibility with respect to decision variable is modeled if output is constant • Due to change in irreversibility, change in cost is decided • Differentiating the cost model with decision variable and equating to zero, optimum condition is obtained.	• Selection of decision parameter is critical • Output is fixed. In case of variable output method is not applicable
6	Evolutionary Programming Method	• Global search technique • Used for single objective function	• Simple method • Sound knowledge of programming and Gaussian random variable is required
7	Extended Exergy Accounting Method	• Extension of the previous method. • Apart from physical and chemical exergy, recycling exergy necessary for ideal zero impact disposal of the equipment should be added. • Labor and capital cost converted in the exergy term called added exergy and included in the total exergy	• Cost optimization is similar to Structural method
8	Exergetic Production Cost Method	• Evaluation of exergy input and output for each unit • Exergetic manufacturing cost function formulated • Thermoeconomic functional diagram prepared • Selection of exergetic incremental linked to the input and output of each unit.	• Exergetic manufacturing cost function given by manufacturer, not available for all type of equipment. • Thermoeconomic functional diagram involves individual judgments.

The above review of literature shows that exergy analysis and exergoeconomics are very useful analytical tools in energy engineering for improving the design, operation and maintenance of energy systems. Both exergy analysis and thermoeconomics may be considered to be general and objective methodologies for analyzing and optimizing energy systems. An exergy analysis identifies the location, cause and magnitude of the real thermodynamic losses (exergy destruction and exergy loss). A thermoeconomic evaluation identifies the location and cause of the cost sources, calculates their magnitude and compares their effects on the costs of the products. All this information, complemented by the engineer's intuition and judgment, assists in the improvement of the efficiency and reduction of the product costs in energy systems by identifying the required changes in structure and parameter values much faster than traditional approaches. Decisions about the design, operation and repair or replacement of equipment are facilitated.

The advantage of thermoeconomics is that it replaces an expensive and subjective search for cost reduction with an objective, well informed, systematic and, therefore, shorter search in which all of the cost sources are properly identified and evaluated. The savings in both engineering and computer time are significant. In particular, application of thermoeconomic analysis to new energy system concepts and complex plants (especially those with important chemical reactions) results in significant savings in design costs and costs of plant products. Compared with engineers using the traditional energy and economic analyses, those applying thermoeconomics develop, in general, a better understanding of the performance of energy systems and the interactions between performance and economics, as well as more confidence in their ability to improve energy systems