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Role of Energy and Exergy Analyses in Performance Improvement and Development of Advanced and Sustainable Energy Systems

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ABSTRACT

There is a growing interest on advanced and sustainable energy systems worldwide. Natural gas, biomass and coal based power generation and integrated energy systems are receiving attention to meet the growing energy demand with reduced pollutants and greenhouse gas emissions. Integrated coal and biomass gasification combined cycle power generation systems are also in use due to increased power generation efficiency and reduced emissions. Natural gas and biomass supplementary firing and hybrid power generation systems are also receiving attention to reduce greenhouse gas emissions. Solar, wind and biomass based power generation systems are also growing due to their sustainable nature. The present paper reviews natural gas, biomass and coal based advanced and sustainable energy systems. The exergy analysis for energy systems is receiving attention due to the ability to analyze a power generation system from quality point of view. The role of exergy analysis for natural gas, coal and biomass power generation systems and the role of operating parameters on performance improvement is also presented.

NOMENCLATURE

av	[kj/kg]	availability
C		compressor
CC		combustion chamber
$\dot{E}x$	[kW]	total exergy
$\dot{E}x_d$	[kW]	exergy destruction
$\dot{E}x_f$	[kW]	fuel exergy (exergy input)
$\dot{E}x_{ch}$	[kW]	chemical exergy
$\dot{E}x_{ph}$	[kW]	physical exergy
GT		gas turbine
$\bar{h}$	[kJ/kmol]	specific enthalpy on molar basis
h	[kJ/kg]	specific enthalpy
HPC		high pressure compressor
HRSG		heat recovery steam generator
LHV	[kj/kg]	lower heating value
LPC		low pressure compressor
$\dot{m}$	[kg/s]	mass flow rate
r_p		gas turbine pressure ratio
PCFB		pressurized circulating fluidized bed combustor
$\bar{R}$	[kJ/kmol K]	universal gas constant
RAFR		relative air fuel ratio
SFR		steam fuel ratio
T	[K]	temperature
TIT	[K]	Turbine inlet temperature
y		molar ratio
y^e		molar ratio of gas occurring naturally in the environment
η		efficiency

Subscripts

$_{comb}$	combustion chamber
$_{ex}$	exergetic (based on second law analysis)
$_{f}$	fuel
$_{i}$	state numbering based on schematic diagram
$_{mix}$	gaseous mixture
$_{ST}$	steam turbine
$_{SF}$	supplementary firing

INTRODUCTION

The global energy demand is growing due to rapid industrialization and economic development in many countries. For sustainable development and to reduce global warming trend, the growing energy demand has to be met with reduced pollutants and greenhouse gas emissions in an environmentally friendly manner. There is a need to utilize all energy sources (fossil and renewable energy sources), to meet the growing energy requirements. The composition and mix of fossil and renewable energy sources depends on the energy resources and policies in a country. In recent years, there is more attention in many countries to utilize renewable energy sources in power generation and to increase the renewable energy share in total energy mix. The oil embargo in 1970's resulted in more focus on solid fuels and this resulted in the development of many advanced combustion technologies for industrial use and for power generation. The fluidized bed combustion technologies and its next generation technologies such as circulating fluidized bed combustion, pressurized fluidized bed combustion are being employed for power generation. From the last ten to fifteen years, there is growing attention and importance to develop advanced and efficient fossil fuel based energy systems on one side and to encourage research and development of technologies to utilize renewable energy sources such as solar, biomass and wind in a big way for power generation around the globe.

The fundamentals of exergy analysis, entropy generation minimization are discussed in detail in the literature [1]. The role of exergy to understand and improve the efficiency of electrical power generation technologies is also reported [2]. The details on the use of exergy to correlate energy research investments and efficiencies are also discussed [3]. The details on exergy analysis for a natural gas combined cycle power generation system are reported [4]. The effect of supplementary biomass firing on the performance of combined cycle power generation system is reported [5]. The second law analysis and its role on the analysis and performance improvement of natural gas fired gas turbine cogeneration systems is discussed [6]. The effect of supplementary firing options on cycle performance and CO_2 emissions for an integrated gasification combined cycle (IGCC) power generation system is reported. The role of operating conditions on power output, plant efficiency and CO_2 emissions are reported [7]. The analysis, modeling and extensive details on hydrogen production from coal gasification for effective downstream CO_2 capture are reported [8]. Parametric exergy analysis of coal gasifier and gas turbine combustion chamber with main focus on emissions are reported [9]. The details and advances in clean coal technologies are presented [10]. The thermodynamic analysis and the role of operating conditions for a coal based combined cycle power plant are reported [11]. The technical details on hydrogen production from coal gasification and the economical pathway to sustainable energy future is presented [12]. The application of pressurized circulating fluidized bed technology for combined cycle power generation is discussed [13]. The exergetic evaluation of biomass gasification and the role of operating conditions are presented with details [14]. The parametric analysis and the role of operating conditions on the performance of a coal based combined cycle power plant are reported [15]. Thermodynamic analysis of full gasification vs fluidized bed combustion with partial gasification on the performance of coal based combined cycle power generation systems are discussed [16]. The technical analysis and comparison of electricity and hydrogen production systems with CO_2 capture and storage are presented with details [17]. The techno-economic evaluation of IGCC power plants CO_2 avoidance in presented with full details [18]. Parametric simulation of combined cycle power plant with more focus on the role of heat recovery steam generation and the role of pinch point on its design is discussed with details [19]. The review on biomass gasification technologies for energy production is reported [20].

NATURAL GAS COMBINED CYCLE POWER GENERATION SYSTEMS

Natural gas combined cycle power generation systems utilizes the gas turbine cycle and steam turbine with a heat recovery steam generator to generate electric power and are receiving great attention and are employed to generate electric power. The natural gas based combined cycle power generation systems are receiving attention in recent years due to increased overall plant efficiency and reduced greenhouse gas emissions. In the literature research investigations are conducted on the performance analysis and improvement of natural gas combined cycle power generation systems. Research investigations are conducted on natural gas combined cycle power generation systems to improve their power output and energy conversion efficiency. The research activities are focussed on combined cycle plant configurations, gas turbine operating conditions, improvement of component designs, steam cycle operating conditions and analysis and design of heat recovery steam generator with single and multiple steam pressure. In the present discussion, the combined cycle power system configuration as shown in figure 1 is considered for the [4]. The authors [4] conducted energy and exergy analyses for a natural gas fired combined cycle power generation system as shown in figure 1 and the role of operating conditions such as gas turbine pressure ratio, gas turbine inlet temperature and steam cycle conditions on combined cycle work output and plant efficiency are reported [4]. The system has main and reheat gas turbine combustion chambers with high pressure and low pressure gas turbines. The research investigation focussed on the role of gas turbine inlet temperatures, pressure ratios, supplementary firing effects on the topping cycle, bottoming cycle and overall combined cycle plant performance in terms of energy and exergy point of view. The energy analysis is conducted for all the components and for the shole plant. From the the combustors energy balance the airfule requirements for a particular gas turbine inlet temperature are estimated for both main and reheat combustors. The isentropic gas turbine efficiency is used to estimate gas temperature from the gas turbine after expansion for both main and reheat combustors. The investigations are conducted for wide range of operating conditions (gas turbine pressure ratio and gas turbine inlet temperature and steam cycle operating conditions). The component isentropic efficiencies and heat losses for the components are also considered in the analysis and in results simulation. The exergy analysis is conducted and the methodology for the components and for the plant to estimate the performance from exergy approach is developed. The effect of operating conditions and plant configuration on exergetic performance is also reported. In another research work [19] the authors conducted parametric simulation for a natural gas combined cycle power generation system with specific focus on heat recovery steam generator. From the energy analysis, methodology is developed to estimate the work output and efficiency for a natural gas fired combined cycle power plant for various operating conditions. The heat recovery steam generator, the effect of pinch point and type of heat recovery steam generator on plant performance is investigated. It has been observed that the type of heat recovery steam generator and pinch point has significant influence on power output and in reducing irreversibilities and entropy generation [19]. The research work in recent years is more focussed on the dual and triple pressure heat recovery steam generator types and their design in improving power output and in reducing irreversibilities.

Natural Gas and Biomass Supplementary Firing Power Generation Systems

There is a growing interest on natural gas and biomass supplementary firing power generation systems. The use of biomass will help to reduce carbon dioxide emissions from natural gas based power generation systems. The extensive research investigations on the use of biomass as a supplementary fuel in a natural gas fired combined cycle power generation system as shown in figure 2 is reported [21]. As shown in figure 2, the plant utilizes both natural gas and biomass in a combined cycle unit. The power output and emissions for this plant depends on the type of biomass and its composition and calorific value. The investigators conducted the energy and exergy analyses and the performance details are reported in the paper. The authors [21] investigated the performance of natural gas and biomass fired combined cycle power generation system with various biomass fuels and supplementary firing options. The effect of gas turbine inlet temperature, gas turbine pressure ratio on plant power output, efficiency and carbon dioxide emissions are investigated. It has been observed from the research investigations and results that there is a potential to reduce up to 20% of carbon dioxide emissions with biomass supplementary firing option for a natural gas based combined cycle power generation system. The power output and emissions depend on the type of biomass used as supplementary fuel with natural gas. The energy methodology developed is useful to analyze the performance of the power plant with biomass supplementary firing, and the effect of biomass type on power output and in reducing the CO_2 emissions compared to same power output based natural gas combined cycle power generation plant.

There is a growing interest on natural gas and solar hybrid combined cycle power generation systems. In this natural is fired in a gas turbine combustion chamber and the gas products are expanded in gas turbine unit generating power. The exhaust gases then go through a heat recovery steam generator where superheated steam is generated. In the bottoming cycle concentrated solar collectors are used to generate saturated/superheated steam using solar energy and this way part of the heat input to steam cycle comes from solar energy part from utilizing gas turbine exhaust gases.

COAL, BIOMASS GASIFICATION ENERGY SYSTEMS

Gasification Combined Cycle Power Generation

There is a growing interest to use coal and biomass fuels in a combined cycle mode for power generation due to its high energy convers on efficiency compared to only gas turbine cycle or steam turbine cycle power generation systems. In an integrated gasification combined cycle (IGCC) the coal or biomass is gasified in a gasifier and the fuel gas is cleaned and is burnt in a gas turbine combustion chamber and the unit is operated in a combined cycle mode. Currently a great deal of attention is paid on the integrated coal and other solid fuel gasification power generation systems with carbon dioxide capture.

Biomass and coal gasification based power generation systems have great potential to generate power at higher efficiencies with reduced greenhouse gas emissions. The gasification of coal and biomass began in 1800s and many developments are reported in the last 200 years. Due to higher power generation efficiency associated with gasification over combustion, there is a growing interest on gasification based power generation systems.

Integrated Gasification Energy Systems

The basic details of integrated coal gasification combined cycle power generation systems are described below. In a gasifier coal or biomass is gasified and the fuel gas is cleaned. The syn gas is burnt in the gas turbine combustion chamber and the system is operated in a combined cycle mode. This results in higher power out and plant efficiency and reduced greenhouse gas emissions. Depending on the gasifier, operating conditions certain fundamental reactions happen inside the gasifier. The main chemical reactions that occur inside the gasifier with appropriate energy conditions are reported [14]:

Exothermic combustion reaction,

$$C + O_2 \rightarrow CO_2, \quad \Delta H = -393.5 \text{ kJ/mol} \qquad (1)$$

Endothermic Boudouard equilibrium process,

$$C + CO_2 \rightarrow 2CO, \quad \Delta H = 172.6 \text{ kJ/mol} \qquad (2)$$

Endothermic heterogeneous water-gas shift reaction,

$$C + H_2O_{(g)} \rightarrow CO + H_2 \quad \Delta H = 131.4 \text{ kJ/mol} \qquad (3)$$

Exothermic hydrogenation gasification,

$$C + 2H_2 \rightarrow 2CH_4, \quad \Delta H = -74.9 \text{ kJ/mol} \qquad (4)$$

Based on the amount of steam available the following reactions may occur within the gasifier and in the water-gas shift (WGS) reactors in the H_2 system.

Endothermic methane decomposition,

$$CH_4 + H_2O \rightarrow CO + 3H_2, \quad \Delta H = 206.12 \text{ kJ/mol} \qquad (5)$$

Exothermic water-gas shift reaction,

$$CO + H_2O \rightarrow CO_2 + H_2, \quad \Delta H = -41.2 \text{ kJ/mol} \qquad (6)$$

At high gasifier temperatures, the sulfur in coal reacts with methane and steam to form hydrogen sulfide in a two-step process and the details are reported in the literature [18, 8].

The extensive details on the simulation of integrated coal gasification combined cycle (IGCC) systems to convert solid fuels into fuel gas to run in combined cycle power generation mode is reported [7]. The IGCC unit for which the work is conducted is shown in figure 3. The basic details on gasification and the related equations, simulated details are reported in the paper [7]. The work also involved in simulating and identifying the supplementary firing option with IGCC unit. The work also identifies the better supplementary firing option based on higher efficiency and work output per unit mass of coal and lower carbon dioxide emissions. The three supplementary firing options with the corresponding fuel used are: (i) partial gasification with char, (ii) full gasification with coal and (iii) full gasification with syngas. The performance of an IGCC system with the above three options is compared with an IGCC system without supplementary firing. The full details on the IGCC unit analysis and simulations are reported in the paper [7].

Biomass Gasification Power Generation

The thermodynamic equilibrium model and exergy analysis for a pressurized circulating fluidized bed (PCFB) biomass gasifier as shown in figure 4 is reported [22]. The biomass in general form is represented by a general formula as $C_{a_1}H_{a_2}O_{a_3}N_{a_4}$. The moisture content in the biomass fuel is neglected in the model formulation and analysis. The reactions are solved at thermodynamic equilibrium. The gasification products contain CH_4, CO, CO_2, H_2, H_2O and N_2. The following is the chemical reaction in biomass gasifier [22].

$$C_{a_1}H_{a_2}O_{a_3}N_{a_4} + \mathrm{a}_5(\mathrm{O}_2 + 3.76\mathrm{N}_2) + \mathrm{a}_6\mathrm{H}_2\mathrm{O}$$

$$\Rightarrow \mathrm{b}_1\mathrm{CH}_4 + \mathrm{b}_2\mathrm{CO} + \mathrm{b}_3\mathrm{CO}_2 + \mathrm{b}_4\mathrm{H}_2 + \mathrm{b}_5\mathrm{H}_2\mathrm{O} + \mathrm{b}_6\mathrm{N}_2 \quad (7)$$

The Eq. (7) represents an overall chemical reaction in a gasifier but a number of competing intermediate reactions take place during the process. A thermochemical model has been developed to predict the gas composition for different biomass types. A simplified numerical method is used to solve the thermochemical reactions in the research work. The details of the gasification model and the simulation details are provide in the paper [22]. They also conducted the exergy analysis to identify the exegy losses and irreversibilities and their variation with gasifier and operating conditions. The system consists of a pressurized circulating fluidized bed gasifier to produce the syn gas from the biomass. The effects of relative air fuel ratio (RAFR), steam fuel ratio (SFR) and gasifier operating pressure is simulated on gas composition, gasifier performance and on efficiency from energy and exergy point of view.

INTEGRATED ENERGY SYSTEMS

The integrated energy systems are receiving lot attention in recent years, as there is scope to generate more power and also other products such as hydrogen, chemicals etc. The integrated energy systems can achieve high efficiencies. Coal, biomass, municipal solid waste etc. could be utilized in these systems. The solid fuel is gasified and the syn gas is cleaned. Hydrogen is separated. This system uses gas turbine unit to produce power. The waste heat from gas turbine exhaust is utilized in a heat recovery steam generator to produce steam and is fed into a steam turbine to produce power. The hydrogen can be used in a fuel cell to produce power. Also depending on the solid waste or fuel the integrated energy system also has the potential to capture carbon dioxide. In the coming years the integrated energy systems will receive more attention to develop them due to high efficiency and performance. Research investigations are conducted for triple cycle power generation systems (gas turbine cycle, steam turbine cycle and vapor cycle) to improve the power output and plant efficiency. Research investigations are also conducted on multi-generation energy systems (combined cycle power, process heat, cooling loads) to improve the energy utilization of fossil fuel based energy systems.

EXERGY ANALYSIS AND ITS ROLE ON ENERGY SYSTEMS

The second law analysis or exergy analysis is receiving great attention due to the ability to analyze a power generation system on a component basis and also as a whole system. Unlike the first law of thermodynamics which talks about energy balance for components or for the whole system, the second law provides insight into the performance of the energy system components and the whole energy system from quality point of view by analyzing the irreversibilities in the components, losses in the components and the performance of them with operating conditions. The fundamentals of exergy analysis, entropy generation minimization are discussed in detail in the literature [1]. The role of exergy to understand and improve the efficiency of electrical power generation technologies is also reported [2]. The work [4] reported the exergy analysis for a natural gas based combined cycle power generation system as shown in figure 1. The research investigations reported the details on exergy efficiency, exergy losses and destruction with various operating conditions. The basic details of exergy analysis as reported [4] are given below. The complete analysis and the methodology and results are reported in the published paper [4].

Exergy Analysis

Once the temperature, enthalpy, and entropy are calculated, the availability is computed using:

$$av_i = h_i - h_o - T_o(s_i - s_o) \qquad (8)$$

The physical exergy rate at each state is the product of the availability at that state, and the corresponding mass flow rate:

$$\dot{Ex}_{ph,i} = \dot{m}_i\, av_i \qquad (9)$$

the chemical exergy rate of the fuel (ex: methane) is calculated using:

$$\dot{Ex}_{fuel,ch} = \left(\frac{\dot{m}_{fuel}}{M_{CH_4}}\right)\left\{\left(g_{CH_4} + 2g_{O_2} - g_{CO_2} - 2g_{H_2O(g)}\right) + \left\{RT_o \ln\left(\frac{(y^e{}_{O_2})^2}{y^e{}_{CO_2}(y^e{}_{H_2O})^2}\right)\right\}\right\} \qquad (10)$$

In a similar manner, the chemical exergy rate of the exhaust gases resulting from a combustion reaction is given by:

$$\dot{Ex}_{ch,exhaust} = \dot{m}_{exhaust}\left(\frac{\bar{R}}{M_{exhaust}}\right)T_o\left\{y_{CO_2}\ln\left(\frac{y_{CO_2}}{y^e{}_{CO_2}}\right) + y_{H_2O}\ln\left(\frac{y_{H_2O}}{y^e{}_{H_2O}}\right) + y_{N_2}\ln\left(\frac{y_{N_2}}{y^e{}_{N_2}}\right) + y_{O_2}\ln\left(\frac{y_{O_2}}{y^e{}_{O_2}}\right)\right\} \qquad (11)$$

where: $y^e{}_i$ is the molar ratio for the environmental component i, and g_i is the Gibbs function of formation for gas i [23].

The total exergy rate at each state is the sum of the physical and chemical exergy rates, neglecting the potential and kinetic exergy effects:

$$\dot{Ex}_i = \dot{Ex}_{ph,i} + \dot{Ex}_{ch,i} \qquad (12)$$

The exergy analysis details for some components of the natural gas combined cycle power generation system described in figure. 1 are listed below.

Gas turbine combustion chamber (including reheat and supplementary firing combustor):

$$\dot{Ex}_{dcomb1,2,SF} = \dot{Ex}_{f1,2,SF} - (\dot{Ex}_{5,7,9} - \dot{Ex}_{4,6,8}) \qquad (13)$$

$$\eta_{ex} = \frac{\dot{Ex}_{5,7,9} - \dot{Ex}_{4,6,8}}{\dot{Ex}_{f1,2,SF}} \qquad (14)$$

Heat recovery steam generator (with and without SF):

$$\dot{Ex}_{dHRSG} = (\dot{Ex}_{8,9} - \dot{Ex}_{9,y}) - (\dot{Ex}_{10} - \dot{Ex}_{13}) \qquad (15)$$

$$\dot{Ex}_{lHRSG} = (\dot{Ex}_{9,y} - \dot{Ex}_1) \qquad (16)$$

$$\eta_{ex} = \frac{\dot{Ex}_{10} - \dot{Ex}_{13}}{\dot{Ex}_{8,9} - \dot{Ex}_{9,y}} \qquad (17)$$

where, $\dot{Ex}_f$ is the exergy rate of the fuel.

RESULTS DISCUSSION

The exergy analysis results provide an idea on the irreversibilities, losses and the role of operating conditions on them and ways to improve the overall unit performance. For a natural gas combined cycle power generation system with multistage expansion and reheat with supplementary firing option as shown in figure 1 [4], exergy analysis is conducted and results are simulated. The role of operating conditions on exergy destruction and combustion chamber performance from exergy point of view and the results are presented in figure 5. The exergy losses/destruction variation with gas turbine inlet temperature is shown in figure 5. The exergy loss/destruction variation with gas turbine inlet temperature is different for different components due to irreversibilities. For the same gas turbine pressure ratio, the behavior of main and reheat combustors is different for different gas turbine inlet temperature to the gas turbine stage 1. The gas turbine exhaust temperature from gas turbine1 depends on its inlet temperature. For the same pressure ratio across the turbine, higher the gas inlet temperature, more work output and higher gas inlet temperature to the reheat combustor. For selected type of gas turbine2 (gas turbine inlet temperature), this results in less fuel requirements in reheat combustor which reduces the irreversibilities and losses. This result in the trend that is reported in figure 5 from exergy analysis for various gas turbine inlet temperatures to gas turbine stage1. The figure 5 provides the behavior of different combined cycle gas components from exergy point of view with gas turbine inlet temperature.

Figure 6 represents the exergy destruction for the main and reheat combustion chambers with gas turbine pressure ratio and gas turbine inlet temperature for the natural gas combined cycle power generation system shown in figure 1 [4]. The exergy destruction behavior in the combustion chambers is different with gas turbine inlet temperature for a particular gas turbine pressure ratio. The results provide an idea on exergy destruction and its variation with operating pressure ratio for both the combustion chambers. The gas turbine blade material and the turbine blade temperature have strong influence on exergy destruction for both main and reheat combustion chambers for the same pressure ratio across them.

The variation of syn gas calorific value with operating conditions for the biomass gasification unit (figure 4) as reported by the authors [22] is shown in figure 7. The biomass gasification model is proposed and the details of the characteristics of biomass gasifier with the focus on relative air fuel ratio (RAFR), steam fuel ratio (SFR), and gasifier pressure as key parameters. The syn gas composition, heating value of syn gas, are evaluated with the thermodynamic and chemical equilibrium equations. The exergy analysis is also conducted to estimate exergy losses, destructions and exergy efficiencies.

In the research work published, the authors [24] developed a thermodynamic model based on energy and exrergy approach to analyze the performance of various components for a natural gas combined cycle power generation system from energy point of view and exergy point of view. The exergy analysis results for different components as reported by the authors in the paper [24] for a natural gas fired combined cycle cogeneration is shown in figure 8. The analysis provides the performance of the components and the overall system. The exergy analysis of the components and the exergy destruction and losses and exergetic efficiency of the components provides the performance of individual components from exergy approach. This also provides the details on scope where there is big scope to improve the design and performance of some components which will greatly improve the overall performance of the power plant. The energy analysis of the components and the power plant will not provide this qualitative performance details for the components.

CONCLUSION

The natural gas combined cycle power generation systems are growing in importance due to higher plant efficiency and reduced greenhouse gas emissions. Research investigations are conducted with various plant configurations, biomass supplementary firing and operating conditions to further improve the performance.

Coal gasification power generation systems with combined cycle power generation (IGCC) are providing the opportunity to generate power with higher efficiencies and with reduced greenhouse gas emissions. Research investigations are conducted to further improve the integrated gasification based combined cycle power generation systems. There is a need to conduct research and to develop advanced solid fuel based energy technologies with carbon capture and storage.

The exergy analysis provides quality details on the irreversibilities, performance of various components in a power plant and for the overall power generation system. The exergy analysis provides the performance of the components from second law point of view and the scope to improve the performance of components and the overall power generation system. The energy analysis has limitation on this. The exergy analysis has great scope in improving the performance of components and power generation systems.

Natural gas and biomass hybrid combined cycle power generation systems are receiving attention due to the potential to reduce greenhouse gas emissions significantly due to biomass use in a hybrid power plant system.

Integrated and multi-generation energy systems (power, process heat and fuels productions) are receiving attention due to improved energy efficiency and ability to reduce greenhouse gas emissions significantly.

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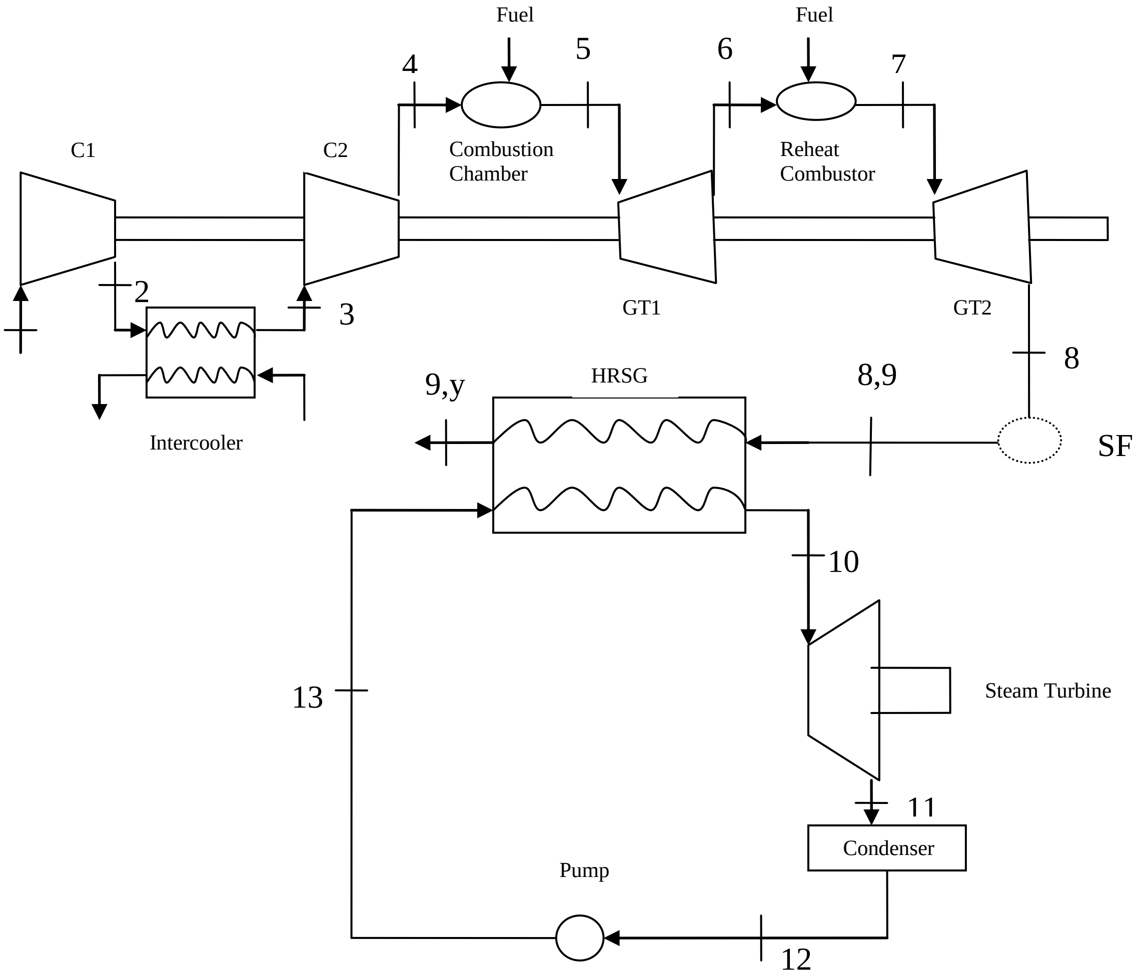

Figure 1 Natural gas combined cycle power generation system [4]

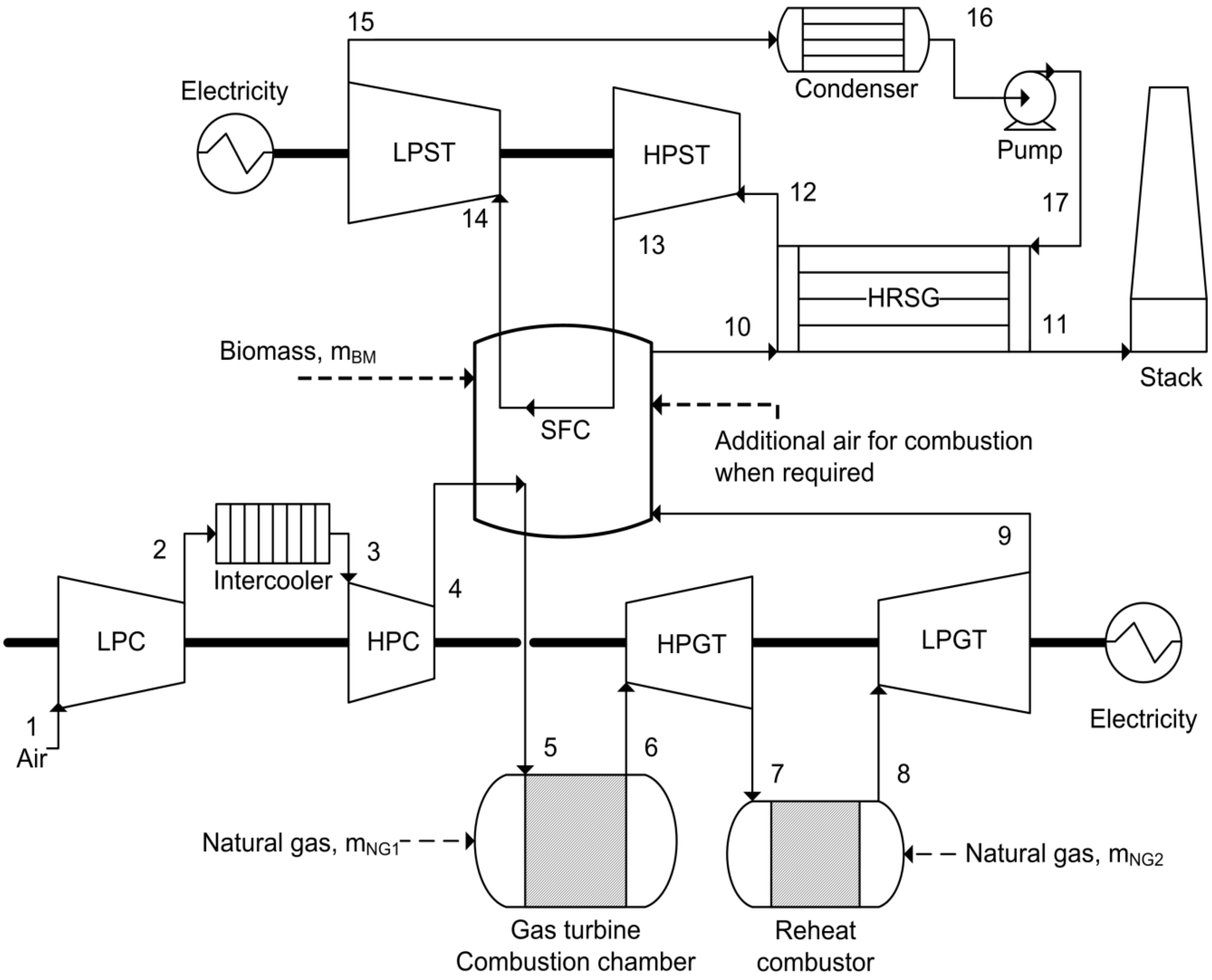

Figure 2 Natural gas fired combined cycle unit with biomass as supplementary fuel [21]

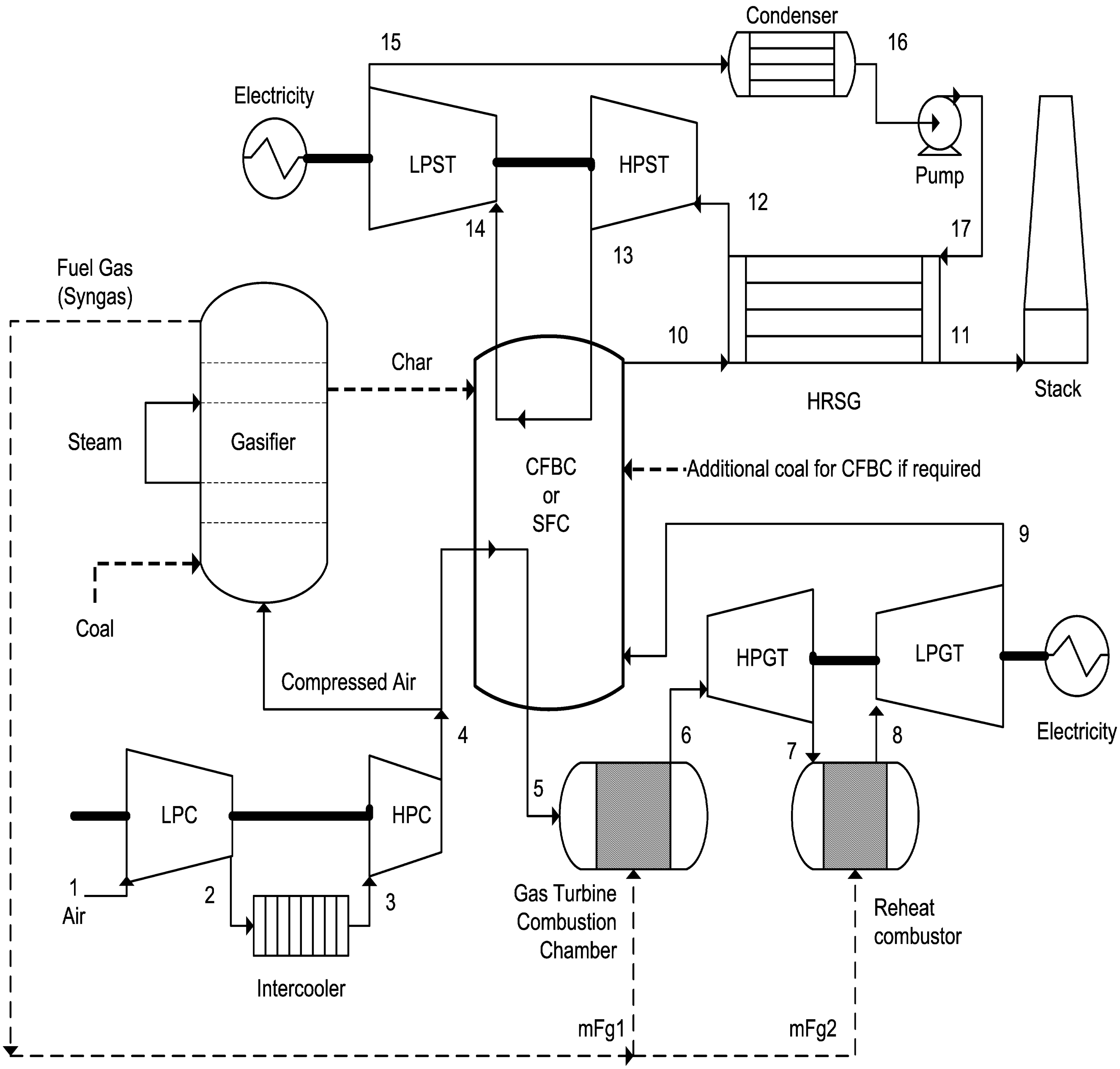

Figure 3 IGCC power plant configuration with CFB combustor or supplementary firing combustor (SFC) [7]

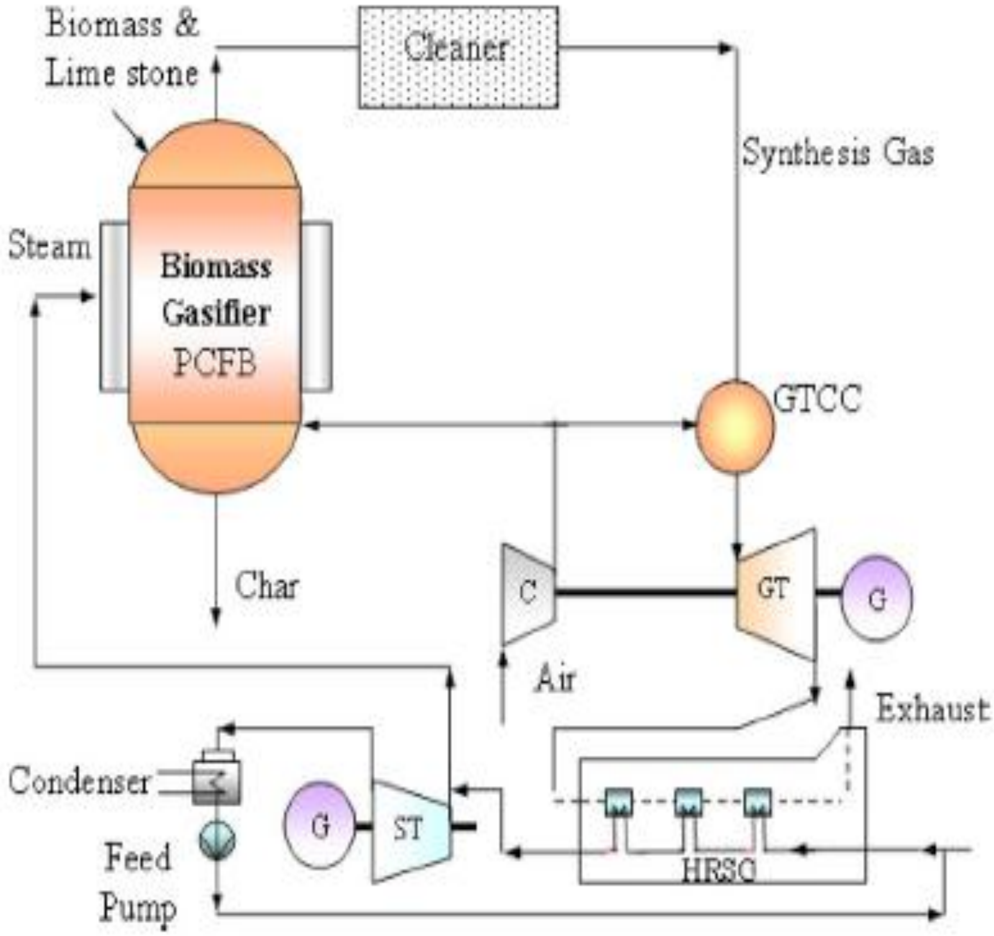

Figure 4 Schematic flow diagram of a biomass gasifier power generation system [22]

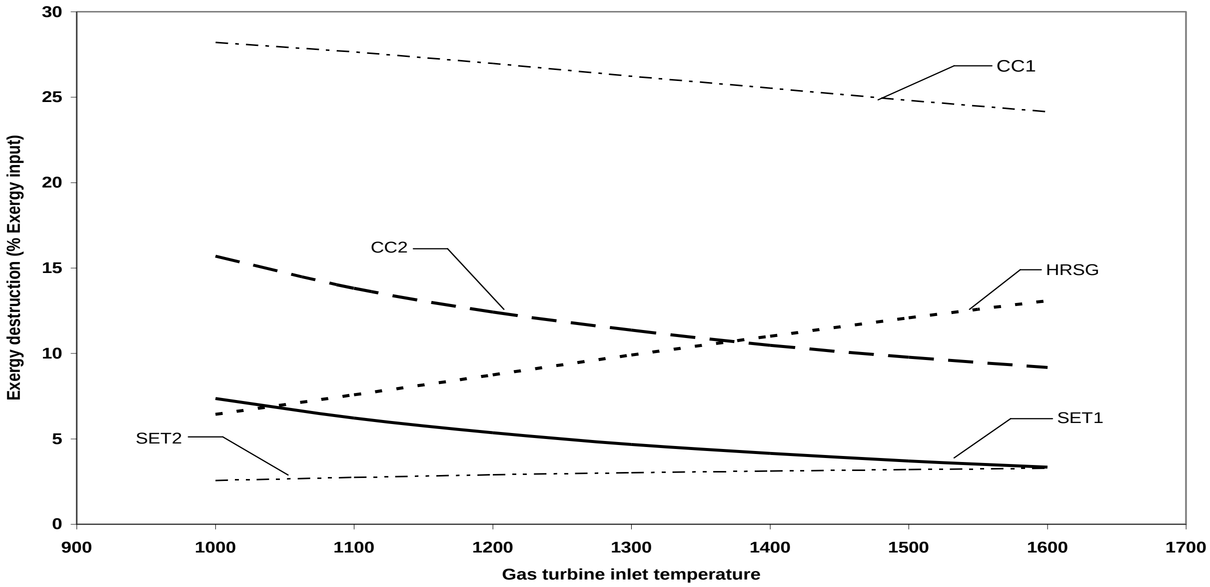

Figure 5 Rate of exergy destruction/losses variation with gas inlet temperature for a particular gas turbine pressure ratio (rp=14), [4],
SET1: Compressors, Intercooler, and Gas turbines, SET2: Steam turbine, condenser, and pump, CC1: Gas turbine main combustion chamber, CC2: Gas turbine reheat combustor

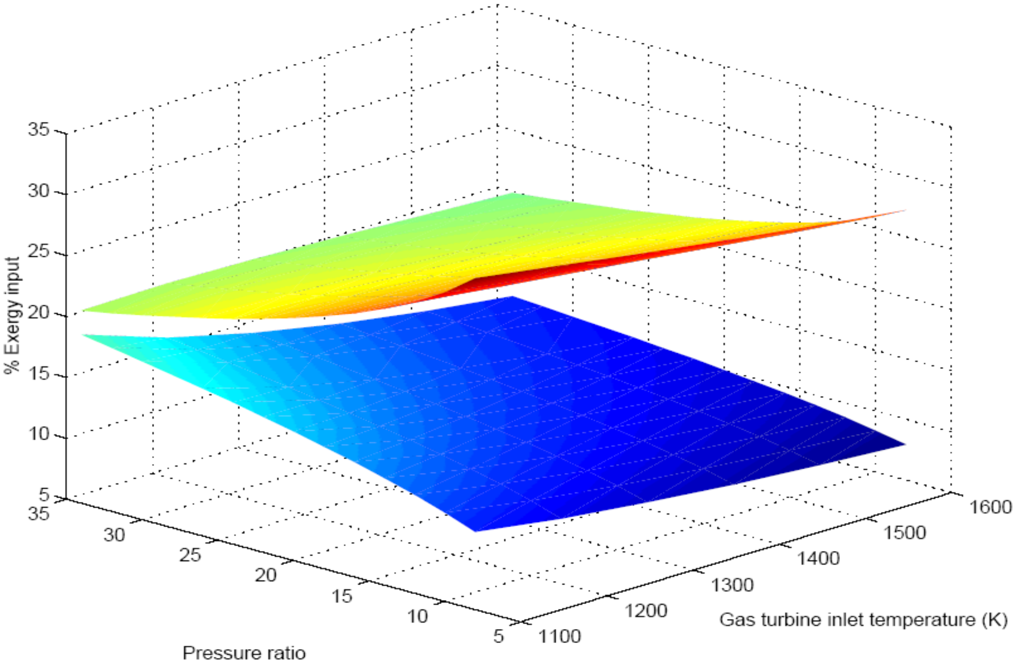

Figure 6 Exergy destruction rate plots for the main and reheat gas turbine combustion chamber [4]

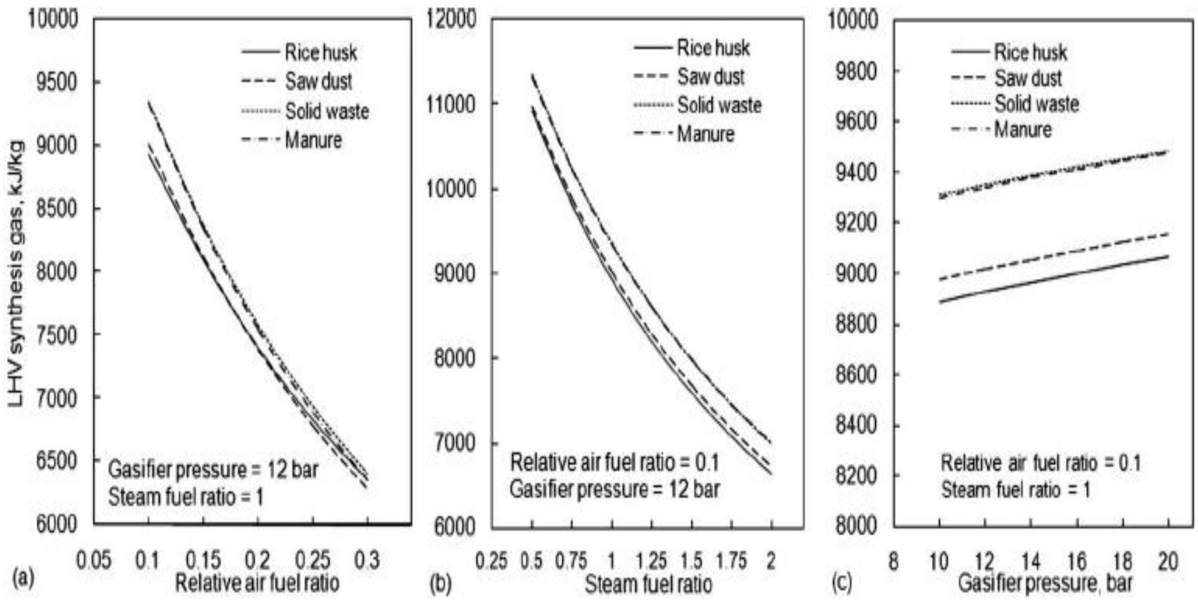

Figure 7 Syn gas LHV as a function of (a) RAFR, (b) SFR, and (c) gasifier pressure for different biomass fuels [22]

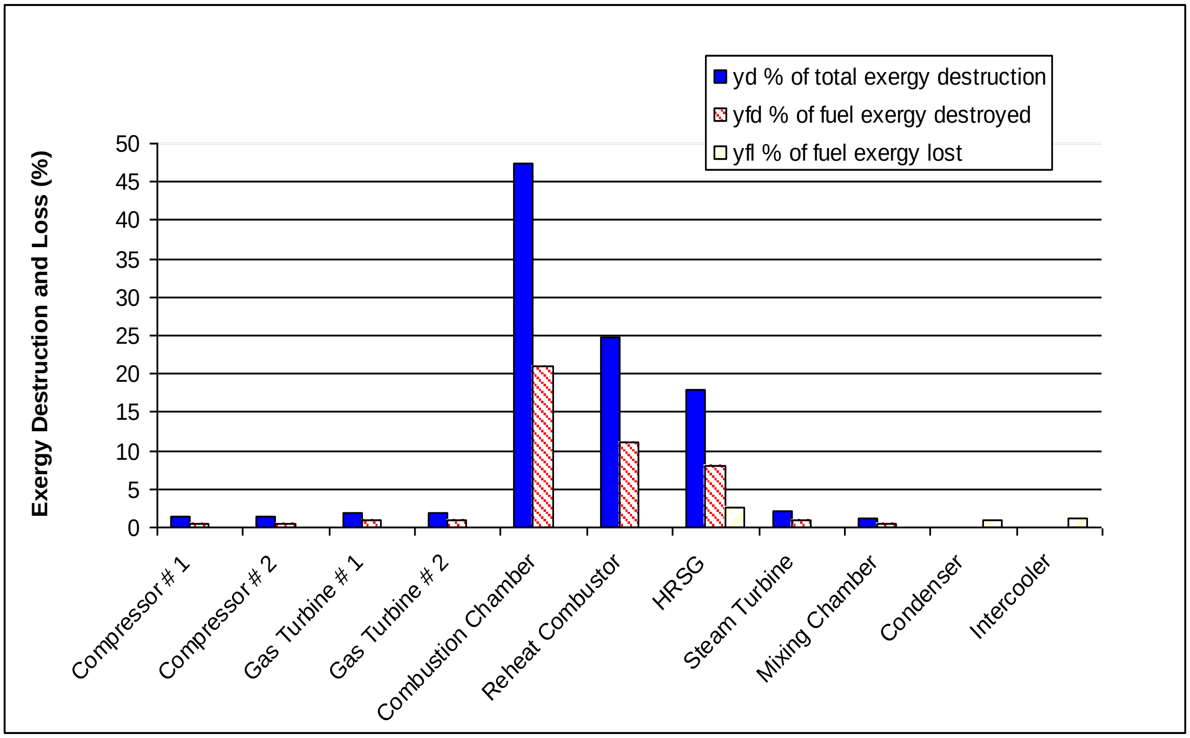

Figure 8 Exergy destruction and loss of all system components
(TIT = 1600K, r_p = 25) [24]