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Exergy in Hybrid Gas Turbines- A Review

Manavalla Sreekanth and Joseph Daniel*

School of Mechanical and Building Sciences, VIT University, Chennai Campus, Vandalur Kelambakkam Road, Chennai - 600 127, Tamil Nadu, India; manavalla.sreekanth@vit.ac.in, joseph.daniel@vit.ac.in

Abstract

Objectives: A review of Exergy based analysis in Gas Turbine-Hybrid systems for power generation has been presented. The purpose of the review is to understand the work carried out earlier and to identify the areas which are not sufficiently addressed. Conventional hybrid systems like Gas Turbine-Steam Turbine systems were considered along with non-conventional systems involving fuel cells, renewable energy systems like solar hybrid, and gasifier based systems. **Methods/ Statistical Analysis:** It is noticed that a huge body of work is available on the Gas turbine-steam turbine systems and relatively low amount of work is available in systems involving renewable energy sources. Several end-use applications such as heat generation, chilling and electricity production is possible based on the heat availability in the gas turbine. Optimization techniques were useful in the many of the Exergo economic studies that are reported in this review article. **Findings:** This studies show that more exergetic destruction happened in combustion chamber and fuel cell stacks owing to the high temperatures involved. Turbine inlet temperatures, compression ratio and air fuel ratio had a major say in the exergetic efficiency of the system. Innovative techniques like steam injection, inlet fogging, partial oxidation were useful for better system efficiencies. Most researchers have pointed at the commonly known parameters like the turbine inlet temperature, compression ratio and turbine exit temperature to be crucial for better exergy performance. However, there are a few researchers who pointed at much more specific areas like the combustion chamber and the HRSG to be the culprits where most exergy destruction happens**. Improvements:** Various techniques of hybridization of gas turbines by conventional and renewable energy systems were suggested by different authors towards capitalizing the benefits of both the systems irrespective of irreversibilities but more work is still needed to reduce the exergy destruction which would be of immense help in improving the energy efficiency and availability of low cost energy.

Keywords: Conventional, Exergy Analysis, Fuel Cells, Gas Turbine Hybrid, Non-conventional, Solar

1. Introduction

Many machines producing mechanical power had been identified and tested so far. Of the various machines turbines were the most satisfactory candidate which has only a few balancing problems. The advantages of turbines were capitalized in hydro turbines first later followed by steam turbines. Power plants of more than 1 GW shaft power with 40% efficiency were on the cards. The steam turbines however demanded bulky and expensive equipments like steam boilers and steam supply units to raise the temperature of water which in turn is fed to the turbines. The hot combustion gases from the fireplace of the boiler never directly reach the steam turbine. They are merely used to produce an intermediately fluid namely steam.

1.1 Development of Gas Turbines

The intermediately heating process however is eliminated in case of a Brayton cycle based Gas turbine (GT) where high temperature gases from the combustion chamber (CC) directly reaches the turbine. The Gas turbines[1] were starting its operation on war front during the Second World War but soon was finding its place in the turbo-jet engines in the domain of aircraft propulsion. The Gas turbine consists of three major components namely a Gas Turbine (GT) compressor(C), combustion chamber (CC). Operationally the high pressure air exiting the compres-

**Author for correspondence*

sor proceeds to a constant pressure combustion chamber where a fuel like natural gas is combusted. The high temperature gases exiting the combustion chamber are sent to a gas turbine where the thermal energy of the hot combustion gases is converted to mechanical shaft power.

1.2 Efficiency Enhancement in Gas Turbines

Various techniques had been adopted to study the performance characteristics of Gas turbine models of which with specific reference to a twin shaft gas turbine model has been analyzed under varying environmental conditions in design and off design conditions and the results revealed that an increase in load causes the gas generator to accelerate which will cause a higher compressor air mass flow rate and compressor pressure ratio[2]. Other intrusive methods like insertion of twisted tapes can increase heat transmission thereby increasing the cooling effect. The blade temperature is decreased by 34% at the leading edge which may increase the efficiency of the gas turbine[3]. On the quest to improve the thermal efficiency the exhaust gases which are at a higher temperature is used to heat incoming air before it reaches the combustion chamber by a process called regeneration. The total work of the Gas turbine cycle is increased by minimizing compressor work by introducing cooling between compressor stages and work output of the turbine increased by multistage expansion of the gas with introduction of reheating in between. Hybridization is one way of increasing the utility of the Gas turbine system especially when the novel aspects of energy such as solar, biomass and fuel cells could work in tandem with the Gas turbine thereby increasing the efficiency. This combined cycle or integrated approach can raise the overall efficiency of the system up to 60%. The durability of such hybrid systems to fast load changes have also made strides in the research front. This review article brings the useful work potential of Gas turbines in two aspects namely gas turbine with conventional energy systems and gas turbine with renewable and nonconventional energy systems.

1.3 Exergy in Gas Turbines

Work potential[4] is a novel way of analyzing the maximum deliverable potential of any energy system based upon the second law of thermodynamics. This is much different from the energy aspects of the first law analysis which focuses only on the system's ability of motion. Exergy analysis had been applied to residential, transportation, industrial sectors and the usage of Exergy is novel to transportation sector. A study in Iran revealed that the value of energy and exergy efficiencies did not vary much in a 24 year period due to the well defined transportation policies[5]. Exergy is conserved in a reversible process where as it is spent in an irreversible process.. Since exergy is not conserved, its destruction is bound to happen. The destruction of exergy in Gas turbines happens mainly due to compression, addition of excess air, combustion at stoichiometric conditions , convective cooling in vanes and blades, expansion, mixing at different process temperatures, various heat losses, transport of shaft work, conversion of mechanical to electrical energy[6].

The framework[7] of Exergy in Gas turbine systems was formulated under standard operating conditions of inlet air temperature at 26°C, pressure of 1.013 bar where pressure increases upon compression to 8.611 bar and a turbine inlet temperature of 1048°C. The isentropic efficiency is 83% and a regenerator to heat the incoming air to compressor operating at an efficiency of 75%. The pressure drop through the air preheater is 4% of inlet pressure for both streams and through the combustion chamber is 3% of inlet pressure. Fuel is injected at 20°C and 30 bar pressure.

2. Hybrid Gas Turbines with Conventional Energy Systems

Hybrid energy is a combination of two or more energy sources for producing power which is used in various utilities. This section reviews the gas turbines with conventional energy systems which are considered as a hybrid system. Depending on the temperatures available at Gas turbine exit and the demand of the utility the hybrid systems are used for various purposes like energy generation by organic rankine cycles, trigeneration where electricity, chilling effect and power generation are realized and desalination of brackish water to produce fresh water.

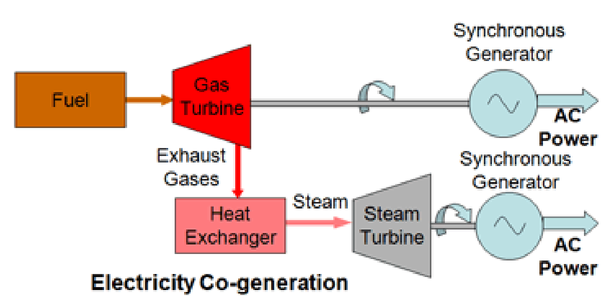

Figure 1. Combined gas and steam turbine system[5].

The most popular method of hybridization[8] is realized by combining the Gas turbine system with a conventional steam turbine in which the former is the Brayton cycled based topping cycle and the latter is the Rankine cycle based bottoming cycle. In this special case as shown in Figure 1, the heat recovered from one electricity generation process is used to generate electricity by another process. The fluid inlet temperature ranges up to 1425°C in gas turbines . The use of higher temperatures is made possible in Gas turbines due to the most recent developments in cooling of turbine blades more effectively and coating the turbine blades with high temperature ceramics. As the average temperature of heat addition goes up the gas turbines have great potential for higher thermal efficiencies. In gas turbines the disadvantages arises due to high temperature of heat rejection which neutralizes the positive benefits attained due to high thermal efficiencies. The situation however can be advantageously used to operate a steam generator in the gas turbine exhaust side to capitalize the high temperature availability. This gives rise to a concept of combined cycle system[9] which uses a gas turbine and a steam turbine in tandem to generate electricity.

Thermodynamic analysis of a gas turbine system and a gas turbine- steam turbine process heat system was carried out based on the first and second laws of thermodynamics approach and engineering evaluation based on levelized cost of energy approach. An algorithm was developed to compute various parameters like combustion gas temperature, compressor and turbine outlet gas temperature, specific work output, mass of air flow, fuel exergy, gas turbine efficiency, costs of each module and the total cost of the system, levelized cost of power and payback period. The simulation results were in good agreement with actual data and by carrying out parametric studies one can determine thermodynamic, engineering parameters and suitable operational conditions[10].

A second law based approach[11] for the analysis of component wise exergy destruction of various cycle components like compressor, gas turbine, combustion equipment, an energy conservation equipment such as heat recovery steam generator, steam turbine and water cooled condensing equipment with respect to the variation of vital parameters like air-fuel ratio and compression ratio showed that elevated values of compression ratio and low air-fuel ratio resulted in lesser exergy destruction with respect to combustion. At optimum conditions the rational efficiencies were 57.48 and 64.39% respectively. For maximizing the plant efficiency it was understood that the Turbine inlet temperature (TIT) has to be as high as 1700 K and turbine exit temperature at 750K

A thermodynamic, exergo economic and environmental assessment[12] of a co generation system consisting of a gas turbine and an organic rankine cycle (ORC) connected through a single pressure heat recovery steam generator was suggested in which the results had shown that most exergy destruction takes place in the combustion chamber followed by the heat recovery steam generator and the gas turbine. The exergo economic factor was found to be 10.59% which is more than the capital investment cost rate. A combined cooling, heating and power (CCHP) system consisting of a small scale gas turbine, an exhaust fired double effect absorption chiller and heat exchanger was analyzed on the basis of exergy and energy by simulating off design conditions. The exergy destruction was reported to be maximum in the combustor and minimum from the exhaust gas from the absorption chiller[13].

Exergy analysis of a dual pressure heat recovery steam generator at HP and LP in 50-70 bar range and 2-6 bar respectively in a Gas/Steam combined cycle power plant for varying dead states is performed in which the superheater section of LP and HP sections of HRSG had substantial exergy losses. In the evaporator section the exergy losses increase for higher dead states and exergy efficiency decreases. The HP evaporator shows remarkable effect of increase in exergy losses by 50% in higher dead states[14].

An exergo economic analysis[15] was conducted in a combined system of 299 MW electrical output where the heat from combined Gas turbine modular helium reactor (GT-MHR) is expended by two organic rankine cycles(ORC's). Various parameters like compressor pressure ratio, turbine inlet temperature, evaporator temperature, pinch point temperature difference were considered. Of all the components precooler, intercooler and organic rankine cycle condenser showed the worst exergo economic performance. The exergo economic factor, capital cost rate and exergy destruction cost rate are estimated to be approximately 38%, 6876 Dollars/h and 11,242 Dollars/h respectively. The electricity cost produced by GT-MHR turbine increases as the turbine inlet temperature increases. A new function[16] on the basis of energy efficiency, cost of exergy and social cost of air pollution based on externalities for an operating system is proposed and upon validation of the system with an actual power plant it was concluded that the usage of inlet fogging system increased the energy and exergy efficiencies and causes a 4% reduction in the objective function value.

Efficiency of a gas turbine system can be increased by various innovative methods apart from the well established methods of intercooling between the compressors and reheating between various turbine stages. Of the various innovative methods injecting steam[17] into the combustion chamber offers various benefits like power augmentation, reduction of NO_x and CO_2 and offer more cooling of turbine blades than if cooled by air. A portion of the generated steam at the gas turbine exit stages are also used to cool the turbine blades directly in a closed loop. Various parameters like steam coolant temperatures, mist fraction, mist temperature, pressure ratio, turbine inlet temperature and blade temperature were studied and their effects upon net work, first and second law efficiency and other relevant parameters like, energy ratio, fuel conversion ratio were analyzed. At 2% of the mist, the exergy efficiency is decreased by 0.04% than that for exergy efficiency of steam only case. Another performance enhancement technique namely POSTIG (Partial Oxidation Steam Injection Gas Turbine)[18] was suggested in which partial oxidation of the fuel which had resulted in staged released of thermal energy from the fuel. The effect of Partial oxidation gas turbine is integrated with gas turbine injected with steam, the resultant Partial oxidation steam injection gas turbine (POSTIG) was investigated based on key variables. On comparison with s Steam injected gas turbine cycle the efficiency is 2% higher and the second law efficiency of the POSTIG cycle is 50.648%.

Exergy based analysis are recognized as proper tools to assess the economic, environmental and social externalities of energy systems like a simple Gas turbine unit based on simple Joule- Brayton cycle. An innovative system was proposed to assess the environmental analysis which combines the exergy and risk analysis. The mentioned method along with standard second law based exergy and thermoeconomic analysis are used to determine the standard configuration of the system with respect to their specific objective function[19].

A correlation[20] between response variables (performance characteristics) and predictor variables (operating parameters) were developed through multiple regression analysis in an attempt to perform a thermo environmental analysis of an Open cycle gas turbine power plant. The optimum values of the operating parameters were found to be 288 K for compressor inlet temperature (TIT), 1600 K for Turbine inlet temperature (TIT) and a PR value of 23.2. It was evident from the above study that the maximum exergy destruction occurred in combustion chamber mainly due to irreversibility that occurs due to combustion reactions and maximum temperature difference that exists in it.

A thermodynamic modeling[21] of gas turbine with absorption chiller is realized with the help of a thermo economic approach to find the optimality of design parameters like compressor pressure ratio, compressor isentropic efficiency, gas turbine inlet temperature, steam generator pressure, pinch point temperature, absorption generator temperature, absorption evaporator temperature and absorption condenser temperature for practical applications. The model has an objective function is a summation of cost of fuel purchase, component wise purchase cost and the total cost rate of exergy destruction. The conclusions indicate that the increase in unit cost of fuel has significant effects towards the selection of the equipments in the direction of decrease in objective function.

Trigeneration[22] is a concept where three different utilities like power generation, heat recovery and chilling effect from a single energy system is envisaged. Upon the first and second law analysis it was reported that the maximum exergy destruction occurred in the combustion and steam generation process. Various parameters like first and second law efficiency of trigeneration, electrical to thermal energy ratio, co generation and gas turbine cycle showed significant variations with the change in overall pressure ratio and turbine inlet temperature whereas change in pressure difference, pressure of the process heat and evaporator temperature showed only small variations in these parameters.

An Energy-Exergy analysis[23] of an intercooled combustion-turbine combined cycle (ICCT-CC) power plant was conducted and it showed an enhanced performance when compared to a simple gas turbine cycle. The cycle efficiency was maximized by the selection of an appropriate interccooling-pressure ratio. It was observed that maximum efficiency of the proposed cycle occurred in lower values of intercooling pressure and maximum work output occurred in higher value of intercooling pressure ratio. Second law analysis showed that the rational efficiency of the combustion-turbine combination was higher by about 3.13% than that of the basic cycle. Exergy destroyed was maximum in the combustion chamber. The summation of all the exergy destroyed in the intercooled cycle is lower by 2% when compared to the basic combustion-turbine cycle. Energy and exergy analysis of a Gas turbine- Heat recovery steam generator (GT-HRSG) integrated with Regenerative Organic Rankine cycle (RORC) in which it was evident that the combustion chamber showed the maximum exergy destruction rate and it can be decreased to 59% upon increasing the combustion chamber inlet temperature and thereby increasing about 4.5% of the exergy efficiency of the system[24]. A multi objective optimization method leading towards the optimization of Abadan combined cycle power plant was suggested and it was found that the efficiency of the plant largely depends upon gas turbine inlet temperature, compressor pressure ratio and pinch point temperature and any change in these parameters were reported to noticeably affect the objective function, the efficiency can be improved after optimization up to 7.12% and heat rate reduced from 7503 kJ/kWh to 7149 kJ/kWh and the exergy destruction showing a reduction of 8.37[25]

2. Hybrid Gas Turbines with Renewable and Nonconventional Energy Systems

Gas turbines can be combined with renewable energy systems like solar, biomass, fuel cell system. Different market researchers have predicted an increasing share in the field of power production with decentralized technologies. Higher efficiencies with lower emissions have a greater value and are set to make strides in the energy market. Combinations of renewable energies both upstream and down stream in a gas turbine had been researched and demonstrated by various research groups and this section brings certain key advancements in the field of hybrid Gas turbine- renewable energy systems.

2.1 Hybrid Gas turbines with Fuel cell systems

Hybrid gas turbine fuel cell system[26] as shown in Figure 2 has two major components namely, a high temperature fuel cell and a gas turbine engine. Electrochemical devices like fuel cells converts the chemical energy of the fuel directly to usable electrical energy, even though similar to batteries that store chemical energy the fuel cells continuously generate electricity on demand with the chemicals. Different fuel cells are available namely Alkaline Fuel Cell (AFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC), Phosphoric Acid Fuel Cell (PAFC), Proton Exchange Membrane Fuel Cell (PEMFC) etc. Of all these types the ones with high temperature fuel cells are suitable for hybrid operations. This allows the integration with gas turbine which is mutually beneficial. Molten carbonate fuel cell operates at 650°C and solid oxide fuel cells are made of ceramic materials and metals and can have a temperature flexibility of upto 1000°C.

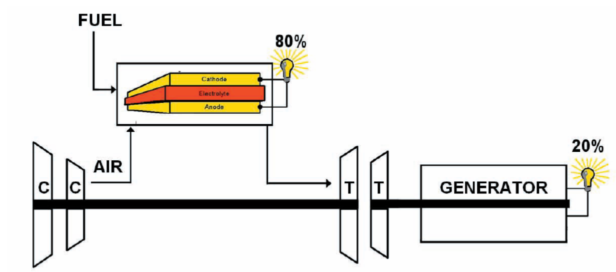

Figure 2. Design concept of a basic gas turbine- fuel cell hybrid system[22].

A typical hybrid system recovers the thermal energy in the exhaust side of the fuel cell and converts it into additional electrical energy through a heat engine. The Gas turbine-fuel cell hybrid system was conceived in the mid 1970's any many combinations had been tested, patented and published.

An exergy analysis[27] on different SOFC based hybrid energy systems for zero emissions revealed that SOFC stack, after burner, and heat recovery steam generator are the key reasons for the exergy destruction in the system. An analysis of methane fed internal reforming solid oxide fuel cell[28] is done on the basis of first and second law of thermodynamics, the system consisted of pre reformer, SOFC stack, a combustor, a turbine, a fuel compressor, recuperator and heat recovery steam generator. Of all these components when the analysis was performed, maximum exergy destruction happened in the SOFC unit (close to 90%) followed by the combustor (close to 58%). At increased flow rates from 1400 to 3600 kg/hr combustor irreversibilities were nearly steady (at 200 kW) whereas the SOFC irreversibilities decreased steeply (from 320 to 220 kW).

An SOFC integrated combined steam and gas turbine power system[29] had been mathematically modeled and the first and second law analysis had been carried out. A parametric study by considering the variations in compressor pressure ratio, fuel firing rate, current density, boiler pressure, steam turbine inlet temperature and usage of additional fuel in the combustion chamber is carried out to analyze the importance of these parameters in the energetic and exergetic performance. The overall system irreversibility was higher at higher boiler pressures and it is lesser at higher steam turbine inlet temperatures.

A multiobjective optimization[30] including exergetic efficiency and total cost rate of the system is carried out for a molten carbonate fuel cell and gas turbine system with energetic, exergetic, economic and environmental stand point TOPSIS decision making method is used in this approach for determining the system optimum design. The overall exergetic efficiency was determined to be 57.1% to the total cost of 0.324 million US dollars per year and the systems' operating pressure had the maximum impact in the overall second law efficiency of the system. A thermodynamic analysis of molten carbonate fuel cell combined gas turbine system[31] is carried out on the basis of first and second law of thermodynamics, the study revealed that the maximum output work of the system was found to be 314.3 kW and the overall energy and exergy efficiencies are found to be 42.89% and 37.75% respectively .

2.2 Hybrid Gas Turbines with Solar Thermal Systems

The use of gas turbines instead of steam turbines in a solar thermal power system is an effective way to address all the key issues of increasing the efficiency, reducing water consumption and seamless dispatch of power from the energy system. Air based turbines saves a lot of water as it is not needed and it also simplifies hybridization. Solar preheating of the air greatly reduces fuel consumption in the combustion chamber part. Despite the advantages no utility scale air based solar gas turbines have not been constructed and lot of technological uncertainties remains. In this regard an exhaustive work on various configurations of these novel systems was conducted on Two turbines SGT 750 and SGT 500. Higher firing temperatures in SGT 750 limited the solar shares below 30% on an annual basis, the low firing SGT 500 allowed solar shares till 63%. Both these turbines chosen in the initial stages are not fully suitable and later on new series of optimized gas turbines were used. It allowed a reduction of levelized cost of electricity between 14-26% at moderate solar shares[32].

Successful demonstration of the technical feasibility of the solar hybrid gas turbine[33] plant was carried out in which a gas turbine is modified and was introduced with solar preheating of the air at the entry of the combustor. Double receiver modules are used one to operate at high temperature and the other at lower temperature. Upon operating at the design values it was concluded that both the predictions and the system test data agreed well.

Algeria's first hybrid solar-gas turbine power plant[34] is studied on the basis on Exergy for every power plant component through cycle tempo software. The power block containing two SGT-800 steam turbines and a SST-Steam turbine, the solar field collecting heat through ET-150 parabolic trough collectors. The first and second law efficiencies based were 56 and 53% respectively. The combustors with least efficiency at 68% are the major destructors of exergy in the overall system. The turbomachines are the most efficient units in the system. While carrying out the energetic and exergetic analysis of a Solar gas turbine power plant in southern Algeria, it was found that regenerator had a direct influence in the production of electricity in various aspects like less use of natural gas, less heliostat field area and also had resulted in a gain of 4.26% exergy efficiency improvement[35]. A thermodynamic analysis is done for a hybrid gas turbine power plant which includes the modeling of various subsystems like solar collector, combustion chamber and the brayton heat engine. The thermal efficiency is the ratio between the total mechanical power to the total heat input rate that has the sum of both the solar heat from the solar receiver and the combustion chamber. It was evident that the irreversibilities are mainly due to all the subsystems that make up the primary cycle. The thermodynamic analysis could also end up as a starting point of optimization studies that involves various objective functions and constraints[36]. The main goal of a work conducted in Turkey[37] is to check the feasibility of using a Hybrid Solar - Gas turbine-PEM based fuel cell system in emergency black out situations in hospital emergency rooms. PV panels of 300 m^2 area on a tiltable plane, PEM fuel cell capacity of 5 kW and hydrogen storage at 55 bar are used in this study. Energy and exergy analysis for a complete year was determined and were found to be 4.06 and 4.25 % respectively. Further an economic study revealed that the levelized cost of electricity was found to be 0.626 $/kWh**.**

A new solar gas turbine cycle system[38] consisting of 3 subsystems such as tower collector system, gas turbine cycle and kalina cycle is considered for the exergy analysis. Kalina cycles generally are used to handle two fluids. The results shows destruction of exergy in solar receiver and in gas turbine increases as Direct beam radiation and concentration ratio rises whereas it decreases in the heat exchanger and if the ammonia concentration reaches 0.8, the exergy efficiency is at its peak**.** A case study of solar-gas hybrid turbine is considered by Khaldi[39] as many of such systems were under construction in MENA region in Spain, the conventional rankine bottoming cycle is replaced with air bottoming cycle for feasibility studies. Reference cases namely without solar energy, steam bottoming and air bottoming cycles. Of the feasibility studies conducted it was concluded that Solar Air bottoming cycle had the maximum first and second law efficiencies at 47.43% and 45.50% respectively.

2.3 Hybrid Gas Turbines with Gasifier Systems

Thermochemical retrieval of Energy from biomass for the generation of electricity by various methods such as combustion, gasification and pyrolysis. Gasification is used especially in large scale applications. The use of biomass in conventional gas turbines however creates problems due to the sensitivity of gas turbines to impure gas, blockage of filters and fuel injectors etc. Expensive gas cleaning systems are to be employed. These problems however can be avoided if the combustion takes place externally. In one such a system[40] developed and tested the pressurized air from the compressor is heated in a heat exchanger prior to its admission into the turbine. The turbine in turn handles air devoid of impurities and the turbine exhaust air is used to combust the fuel in the combustion chamber. This cycle can use low cost, dirty fuels. The penalty due to the dirty exhaust is paid only by the heat exchanger which is easier to manage than the turbine. The biggest challenge was to design a suitable heat exchanger which can deliver the sufficient inlet temperature fluid to the turbine at the same time handle the exhaust. Upon estimating various exergy efficiencies of the key components such as compressor, turbine and heat exchanger remained higher than 90% whereas the combustion chamber, gasifier efficiencies were less. The identifiable reason for this is due to irreversibilities pertaining to the chemical reactions

A modified model[41] by combining a gas turbine, gasifier and an organic rankine cycle (ORC) which was thermodynamically and economically analyzed based on various parameters such as gasification temperature, combustion temperature, turbine inlet temperature (TIT), the component wise isentropic efficiencies, compressor pressure ratio and maximum ORC pressure. Total cost rate and exergy pressure are selected as two main objective functions. The exergy efficiency was estimated to be 15.6% which can be increased to 19.9% under optimal conditions**.** A hybrid plant comprising of a two staged gasifier, solid oxide fuel cells and micro gas turbine[42] was proposed based on energy and exergy with a special focus on thermal management. The gasifier reactor had the highest destruction of available energy but still had reached 87% efficiency, 28% of the total exergy loss took place in the heat exchangers, 11% in turbomachinery, 10% in the burner and 11% was lost through the exit of the flue gas. Exergy destruction attributable to the SOFC stack was a mere 5%.

Two types of solar collectors namely heliostats and parabolic trough collectors[43] are used to supply heat for biomass gasification and pyrolysis at temperatures in two levels at 1150 K and 643 K) respectively, the reformed syngas is fed to a SGT 900 type gas turbine and the exhaust of the gas turbine is used in a steam generator with a heat recovery system for raising steam for operating a steam turbine. The total exergy loss is reduced by 19.3% when used as a two stage gasifier instead of a single stage system.

On integrating biomass gasifier with a gas turbine system, inlet cooling[44] was considered as an apt method to improve the gas turbine performance during hot and humid months of the year. Upon conducting the first and second law analysis of this system it was found that increasing the pressure ratio of the compressor and the gas turbine inlet temperature raises the respective first and second law based efficiencies. Of all the components gas turbine was found to have the highest exergy efficiency and combustor had the lowest. The proposed system had a lower unit cost of power production when compared to a system running with natural gas

3. Conclusion

Gas turbines are versatile and efficient machines and are considered attractive these days as hybridization or combination with other energy systems are seamless and more feasible. Apart from this it has inherent advantages of using a wide variety of fuels thereby making it easy to integrate with novel renewable energy systems like gasifiers. The high heat availability at the turbine exhausts can be used for power generation in a secondary steam cycle, cooling purposes and other heating purposes. The following conclusions are derived after the review of the hybrid gas turbine systems

1) Various parameters compressor pressure ratio(PR) , isentropic efficiency of the compressor, gas turbine inlet temperature (TIT) , steam generator pressure, pinch point temperature set to play a key role and functionality of the hybrid gas turbine systems. Of which Turbine inlet temperature was a key parameter influencing the efficiencies of the energy generating systems. The turbine inlet temperature should be kept maximum and turbine exit temperature to be kept minimum for maintaining irreversibilities lower. Higher pressure ratios caused more irreversibilities.

2) High compression ratio values and low air-fuel ratio resulted in minimum destruction of exergy with respect to the combustion.

3) Maximum loss of available energy or Exergy, occurred in combustion chamber mainly due to irreversibility that occurs due to combustion reactions and also in the heat recovery steam generator (HRSG) which happens to be the main linking factor of Gas turbine with a secondary rankine based power cycle.

4) Novel techniques like mist injection to steam coolant and partial oxidation steam injection gas turbine technique (POSTIG) are used for exergy efficiency enhancement.

5) Of all the fuel cells systems SOFC and PAFC fuel cells are suitable for integrating with gas turbines and the overall pressure is the controlling factor identified for the exergy efficiency of the system and maximum exergy destruction happens in the SOFC system.

6) On integrating a solar thermal energy system based on heliostats, higher firing rate of the turbines caused reduction in solar shares thereby reducing the initial investment cost and maximum exergy destruction happened in the combustor of the systems. Also it was evident that more subsystems caused more irreversibilities to occur. Exergy destruction in solar receiver and in gas turbine increases as Direct Normal radiation (DNI) and concentration ratio increases.

7) Upon estimating exergy efficiencies of various components of the gasifier and gas turbine energy system, the exergy efficiency of compressor, turbine and heat exchanger remained above 90% whereas it is lesser for combustion and gasifier mainly due to the irreversibilities associated with the chemical reactions. It is thus evident that the attention towards research and development is to be towards the combustion systems and high temperature links in between the gas turbine and other energy systems (both conventional and renewable) for the minimization of irreversibilities and maximizing exergy efficiencies.

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