Thermodynamic Analysis of Solid Oxide Fuel Gas – Gas Turbine using MATLAB

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Abstract— In this paper a comprehensive review has been reported in the field of gas turbine based cycle with their various integration system and analysis. Gas turbines have been used in wide ranging applications since their world's first use in aviation and power generation in the jet engine powered flight and power generation plant since 1939. The high temperature exhaust gas from gas turbine can be utilized in other cycles i.e. Rankine, Brayton for additional power generation or for heating and cooling purpose (cogeneration/regeneration). The analysis shows that the resulting maximum efficiency of this GT-combined system can be up to 90% depending upon the operating condition and configuration used. In addition, a comparative performance evaluation of various cycles is presented clearly showing ranges within which a particular arrangement can be beneficial in power generation sector.
Key words: Gas turbine, Co-Generation, Thermodynamics, Heat, Power

I. INTRODUCTION

In the power generation market worldwide, gas turbines are becoming preferred choice because of their high cycle efficiency, small installation time, and low level of CO_2 emissions [1] and single digit NOx emissions compared to the other power generating systems. In the coming years, advances in the gas turbine technologies combined with innovative modifications to the Brayton cycle, such as, Cascaded Humidified Advanced Turbine (CHAT) cycle, advanced Integrated Gasification Combined Cycle (IGCC), GT and high pressure solid oxide fuel cell (SOFC) hybrid cycle, and combination of high pressure SOFC with inter-cooling, Humid Air Turbine (HAT) cycle, etc. are expected to provide gas turbine based power plants with plant efficiency of 75%. Gas turbine technology with fuel flexibility and comparatively lowest cost/kW will play an important role in coming decades in the power generation market. In the field of energy generation, gas turbines have often been chosen in the past when fast start and shut down on demand is required. This is especially needed for compensating peak loads over the daytime. In contrast, steam cycles as used for coal and oil firing or nuclear power are base-load machines since the start and shut down is tremendously longer due to the large heat capacity in the cycle [2].The basic gas-turbine cycle has low thermal efficiency, so it is important to look for improved gas turbine based cycles [3]. Therefore, enhancing the performance of Gas turbine was successful through raising the turbine inlet temperature (TIT) and the compressor pressure ratio and advances in cooling technology and material science caused high turbine inlet temperature conceivable.
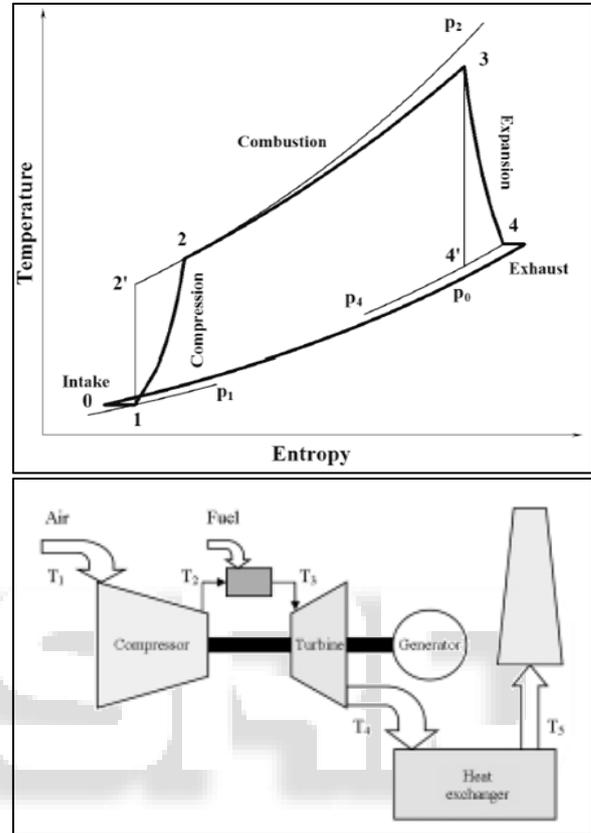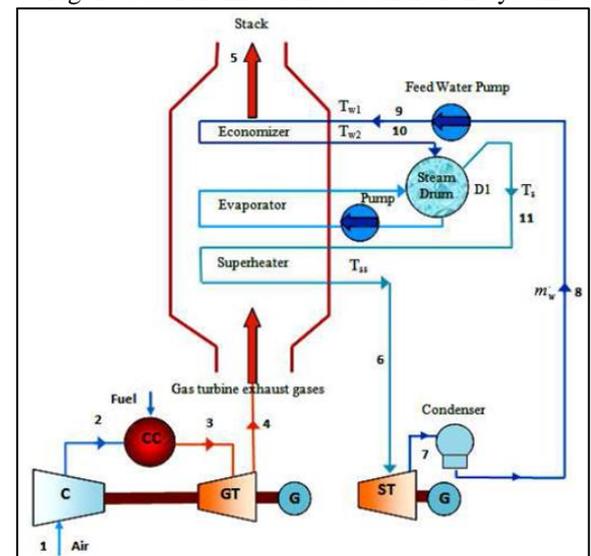
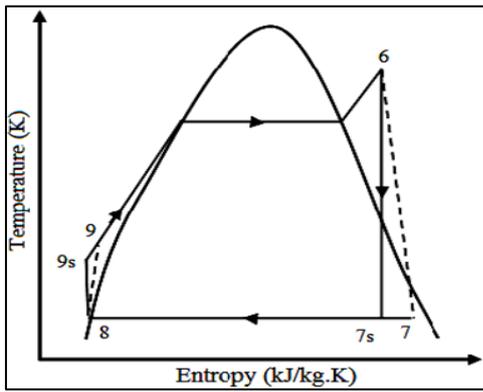

Fig. 1: Gas Turbine with Co-Generation System

Fig. 2: The Schematic of a Single-Pressure Combined Cycle Power Plant and Temperature-Entropy Diagram for Steam Turbine

II. LITERATURE REVIEW

Elwekeel and Antar [2] investigate the addition mist to steam as coolant fluid in steam injected gas turbine for co-generation purpose. The energy and exergy analysis has been carried out and the papramteric analysis has been carried out parameters such as steam coolant temperature, mist fraction, mist temperature, pressure ratio, turbine inlet temperature and blade temperature. The effect of these parameters on system performance has been evaluated and found that the efficiency can reach 47.2% at low coolant temperature with a mist fraction of 2%. The coolant heat gain is enhanced at lower mist temperature, so the blade surface temperature can be improved with mist addition to steam. At a mist fraction of 2% exergy efficiency is decreased by 0.03% than that for exergy efficiency of steam only.
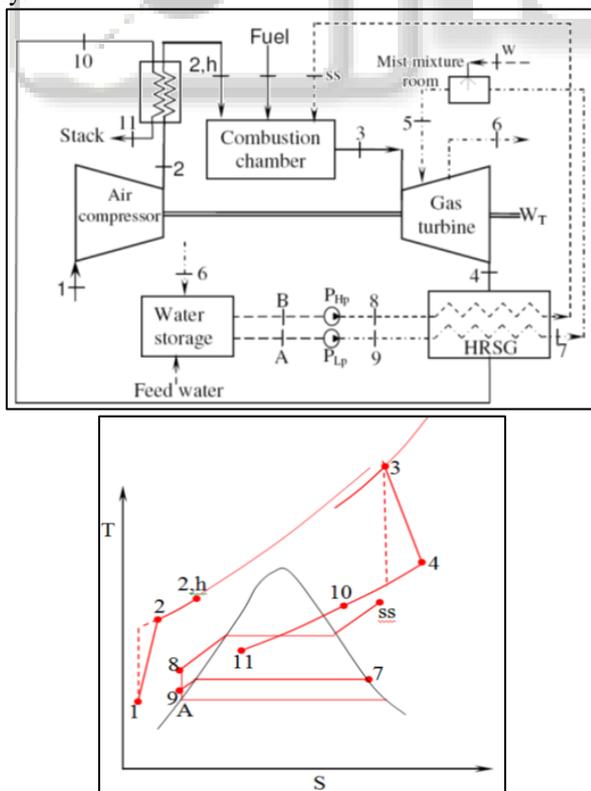

Fig. 3: Schematic Diagram of Modified Cycle and T/S Diagram [2]

Ramakrishnan and Edwards [3] applied systematic irreversibility minimization approach in regenerative gas turbine engines to maximize the efficiency It considers engine architectures that employ two kinds of energy transfers: heat and work. It does not assume any cycle a priori (e.g., heat-recuperative reactive Brayton cycle). Instead, the maximum-efficiency architecture is directly deduced from first principles. Not surprisingly, the optimal architecture has some conventional features such as regenerative heat transfer from post-expansion combustion products to post-compression air, and external heat transfer out during compression (intercooling). But additionally it has three non-conventional features. First, unlike conventional heat recuperation heat is withdrawn between expansion turbine stages and transferred to post-compression air. Second, air is further compressed after heating. Third, compression is required to be part intercooled and part non-intercooled.

Lv et al. [4] use novel technique to determine safe zone for an intermediate-temperature solid oxide fuel cell and gas turbine hybrid system. The system is powered by biogas and a safe map is obtained to overcome from component malfunctioning. Results show that the hybrid system can achieve a high efficiency 60.78%, which is an interesting reference for distributed power stations. In the safe zone, the system has a characteristic of high efficiency and low load with low rotational speed, vice versa. In other words, the powers and load adjustment ranges both decrease with decreasing rotational speed whereas the efficiency increases, which peaks at 63.43%.
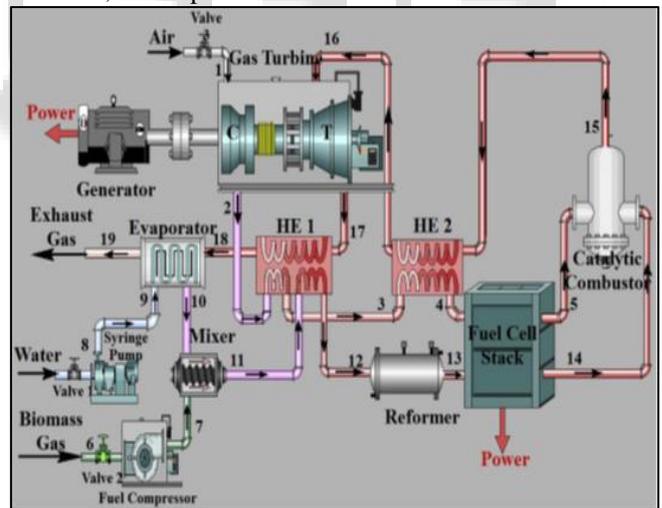

Fig. 4: Schematic of IT-SOFC/GT Hybrid System, C: Compressor, T: Turbine, HE: Heat Exchanger [4]

Khaljani et al. [5] perform multi objective optimization to optimize cogeneration system consists of a gas turbine and an ORC (organic Rankine cycle) in which the two cycles are connected through a single-pressure HRSG (heat recovery steam generator). Optimization results indicate that exergy efficiency of the cycle increases from 51.4% at base case to 56.15% at the optimized condition while more than 12.98% reduction is achieved in the total cost rate of the system. Also, by applying multi-objective optimization method, the exergo-economic factor has reached from 10.68 to 28.54 suggesting that optimum system is achievable when the system costs are due to the

investment costs. Furthermore, it is found that the gas turbine inlet temperature has important role on the trade-off between exergy efficiency and cost criteria.
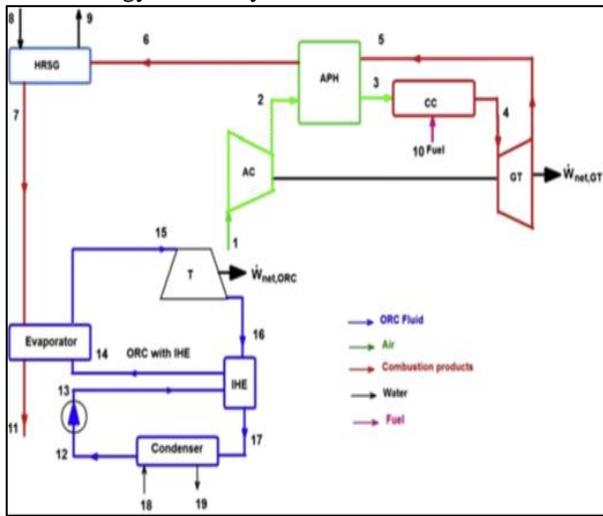

Fig. 5: Schematic Process of Cogeneration Cycle of Heat and Power GT-HRSG/ORC [5]

El-Masri [6] points out two important losses in a gas turbine cycle: (1) the first one is exergy destruction associated with the combustion process. This loss decreases as the mean combustion temperature is increased either by increasing the value of TIT or adding another combustion process (such as reheat); (2) the second source of exergy destruction is associated with the hot gas path component cooling related which will accompany with increase in TIT or with the implementation of reheat increases.

Najjar [7] investigates a novel inlet air cooling systems called the indirect evaporative cooling system (IECS). The system is integrated with a humidifier with a vapor compression or absorption cooling system. The net power produced from the gas turbine on a hot day (45 °C) by using combined (IECS) with absorption chillers showed an increase in power and efficiency by 15% and 9%, respectively; its recovery period is suitable for all environmental conditions. For IECS combined with vapor compression mechanical chillers showed an increase in power and efficiency by about 7.81% and 2.24%, respectively, but its recovery period made it suitable only for hot and humid conditions. The IECS has lower chiller's capital cost by about 25% (mechanical chiller) and 40% (absorption chiller).

Alok and sanjay [8] focused on the comparison of impact of two different methods of inlet air cooling (vapor compression and vapor absorption cooling) integrated to a cooled gas turbine based combined cycle plant. Air-film cooling has been adopted as the cooling technique for gas turbine blades. A parametric study of the effect of compressor pressure ratio, compressor inlet temperature $(T_{i,C})$, turbine inlet temperature $(T_{i,T})$, ambient relative humidity and ambient temperature on performance parameters of plant has been carried out. Optimum $T_{i,T}$ corresponding to maximum plant efficiency of combined cycle increases by 100 °C due to the integration of inlet air cooling.
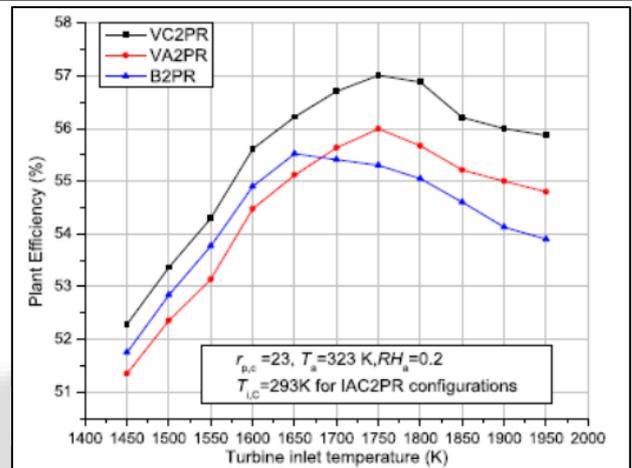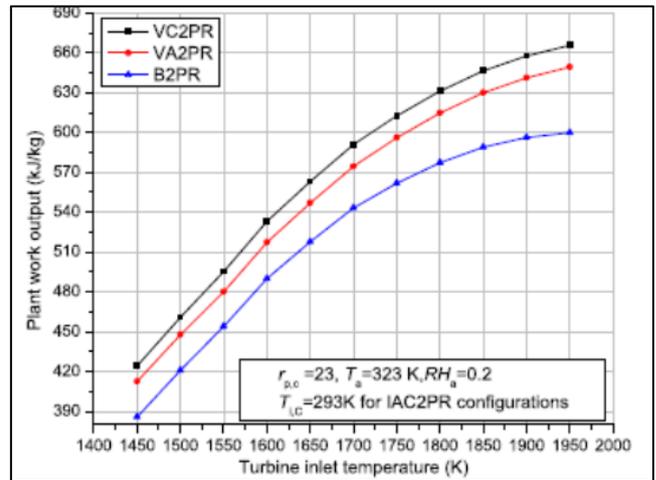

Fig. 6: Variation of Plant Work Output with $T_{i,T}$ for 2PR Cycles with and without Inlet Air Cooling and Variation of Plant Efficiency with $T_{i,T}$ for 2PR Cycles with and without Inlet Air Cooling. [8]

It has been observed that vapour compression cooling improves the efficiency of gas turbine cycle by 4.88% and work output by 14.77%. In case of vapor absorption cooling an improvement of 17.2% in gas cycle work output and 9.47% in gas cycle efficiency has been observed. For combined cycle configuration, however, vapor compression cooling should be preferred over absorption cooling in terms of higher plant performance. The optimum value of compressor inlet temperature has been observed to be 20 °C for the chosen set of conditions for both the inlet air cooling schemes.

Horlock et al. [9] have argued that the efficiency benefits of higher temperatures may be more than offset by the increased losses associated with the large cooling flow rates required. Also increasing $T_{i,T}$ increases NOx emission and hence necessary control mechanism must be employed to keep this NOx emission within permissible limits. This increase in coolant mass flow requirement with the adoption of higher $T_{i,T}$ can be substantially reduced by the integration of inlet air cooling systems to gas turbines and combined cycle plants. It is therefore interesting to investigate the effect of integration of inlet air cooling to cooled gas turbine based combined cycle plan.

Alhazmy and Najjar [10] have analyzed the inlet air chilling using a cooling coil and observed that the

cooling coil improves the turbine output by 10% during cold humid conditions and by 18% during hot humid conditions. However, net power generated from the plant drops by 6.1% during cold and humid conditions and 37.6% during hot and humid conditions.

Louis et al. [11] have compared closed loop and open loop cooling with air, water and steam as cooling medium based on a mathematical model developed. The performance with air cooling is reported to be very sensitive to the difference between turbine inlet and blade temperature and also to the blade heat exchanger effectiveness.
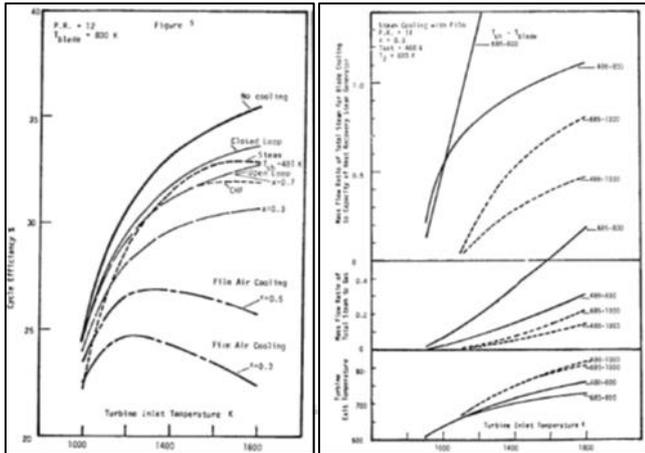
Fig. 7: Variation of Cycle Efficiency and Mass Flow Ratios of Steam Flows and Turbine Exit Temperature as a Function of Turbine Temperature [11]

Chuan and Louis [12] have presented a comparative study on the influence of different means of cooling on the performance of combined cycle by developing a cooling model. The performance of combined cycle using steam cooled gas turbine particularly film steam cooling has been found to be very favorable.

Soltani [13] performs thermodynamic analyses of an externally fired gas turbine combined cycle integrated with a biomass gasification plant, using energy and exergy approaches. The cycle is operated at a wide range of pressure ratio (7–12), gas turbine inlet temperature (1200–1400 K) and heat exchanger cold-end temperature difference (245–275 K).
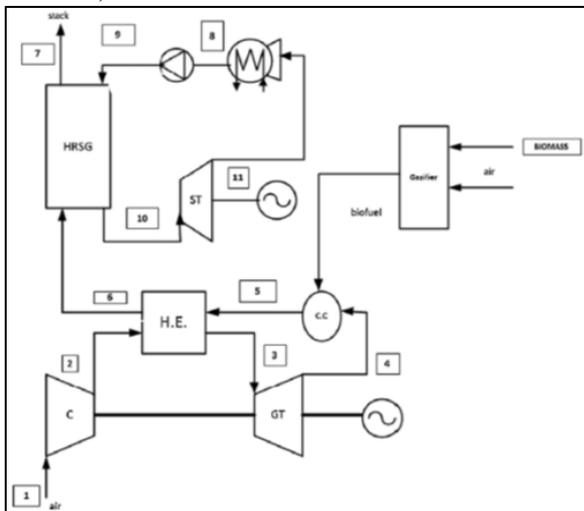

Fig. 8: Schematic of the EFGT/CC plant [13].

Depending on the gas turbine inlet temperature and heat exchanger cold-end temperature difference, the system overall energy efficiency is examined to attain a maximum at a particular pressure ratio. For a specified pressure ratio, the energy efficiency increases with gas turbine inlet temperature and decreases with heat exchanger cold-end temperature difference. An increase in pressure ratio results in a decrease of air flow rate and an increase of steam flow rates. These flow rates are attributable to the size of combined cycle plant. Raising the gas turbine inlet temperature reduces the air flow rate. The performance of a 1 MW plant is investigated with various operating parameters to obtain component ratings and biomass feed rates. Exergy efficiencies of cycle components are examined along with the major thermodynamic irreversibilities.

Godoy et al. [14] presents the optimal designs of a CCGT power plant characterized by maximum second law efficiency values are determined for a wide range of power demands and different values of the available heat transfer area. These thermodynamic optimal solutions are found within a feasible operation region by means of a non-linear mathematical programming (NLP) model, where decision variables (i.e. transfer areas, power production, mass flow rates, temperatures and pressures) can vary freely. Technical relationships among them are used to systematize optimal values of design and operative variables of a CCGT power plant into optimal solution sets, named here as optimal solution families. From an operative and design point of view, the families of optimal solutions let knowing in advance optimal values of the CCGT variables when facing changes of power demand or adjusting the design to an available heat transfer area.

Carapellucci and Adriano [15] analyzed the reheat gas turbine with a methane steam reformer. A modification has been done to the methane conversion rate in the reforming process and, therefore, the efficiency in recovering waste exhaust heat from the gas turbine.
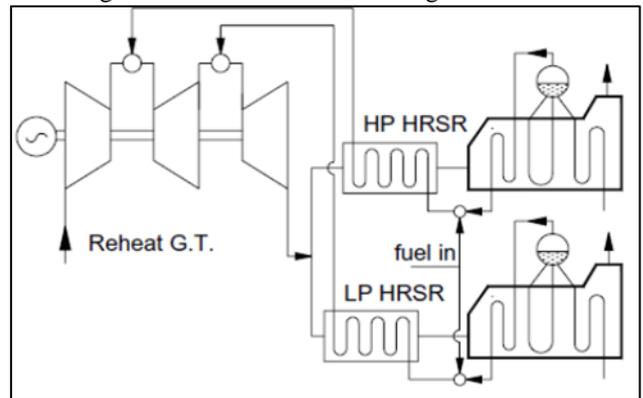

Fig. 9: Scheme of the CRGT plant [15]

Two solutions are recommended for the heat recovery design: a first reformer has a single pressure level whereas the second has two in order to match the different pressures of the combustors. It has found that the single pressure system gives good performance with respect to the stand alone gas turbine; the dual pressure reformer can give a further benefit, as far as an accurate optimization of the steam management is executed.

III. CONCLUSIONS

Exclusive review has been carried out in the field of thermodynamic analysis of gas turbine base cycle. From the studies it has be revealed that various parameters are used to enhance the thermodynamic efficiency of a power plant. Parameters such as compressor pressure ratio, turbine inlet temperature, co-generation system, steam injection in combustor, intercooled gas turbine, integration to various CHP such as solid oxide fuel cell, power turbine, Rankine cycle, steam turbine, etc. Moreover, various optimizations have also been carried out to optimize the combine GT based cycle by utilizing waste heat in bottoming cycle and co-generation. Most of the researcher has focused on energy and exergy analysis but some of them considered economic analysis to make plant more economical.