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Short Communication

Thermodynamic Analysis of a Combined Heat and Power System

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Abstract

In the present analysis combustion products coming out from the gas turbine (GT) are studied on the basis of their concentration. A computer program is made in EES and different parameters are studied for the analysis. From the result it is observed that if regenerator is used in the gas turbine cycle then the concentration of N_2 and O_2 is 0.91% and 1.41% higher respectively in flue gases than that of GT cycle without regenerator. The concentration of CO_2 and H_2O is 2.17% and 17.64% lesser respectively in flue gases for GT cycle with and without regenerator. As the fuel is the combination of the carbon and hydrogen, after burning with oxygen it generates heat energy, CO_2 and H_2O. That is why concentration of H_2O and CO_2 in combustion product increases and that of oxygen decrease. Results show that enthalpy of combustion products at a temperature of 155°C is -28077 kJ/kmol for GT cycle with regenerator and for without regenerator enthalpy is -28027 kJ/kmol at a temperature of 389°C. From the results it may be concluded that regeneration not only increases the efficiency of GT cycle but generates a concentration of N_2, O_2, CO_2 and H_2O in such a manner that enthalpy of combustion gas is increased. Regenerator lowers the exergy destruction in the cycle and increased the fuel utilization efficiency for the cycle. Exergy destruction in most of the thermal systems is due to combustion/chemical reaction, heat transfer and friction including unrestrained expansions of gases and liquids. The inefficiency of combustion may be reduced by preheating the combustion air and reducing the air fuel ratio.

Key words: Gas turbine, exergy, regenerator, nitrogen, oxygen, CO_2 and H_2O.

Introduction

Presently gas turbine cycles have low cycle efficiency. Other things being equal, that is, for ambient air temperature, turbine inlet temperature and cycle pressure ratio, the work per unit mass of gas is a direct function of specific heat (C_p) and more work is produced with higher value of specific heat ratio.[1] Natural gas (methane) produces nearly 2% more output than does distillate oil. This is due to the higher specific heat in the combustion products of natural gas, resulting from the higher water vapor content produced by the higher hydrogen/carbon ratio of methane. This effect is noted even though the mass flow (Kg/h) of methane is lower than the mass flow of distillate fuel. Here the effects of specific heat were greater than and in opposition to the effects of mass flow.[2] Butcher and Reddy[3] investigated the performance of a waste heat recovery power generation system based on second law analysis for various operating conditions. The temperature profiles across the heat recovery steam generator (HRSG), network output, second law efficiency and entropy generation number were simulated for various operating conditions. The variation in specific heat with exhaust gas composition and temperature were accounted in the analysis and results. STIG and regeneration may be used to improve cycle performance. The effect of regenerator on the specific power curve is only to reduce them somewhat because of the added pressure losses in the regenerator.[1] Kotowicz and Bartela[4] studied the influence of fuel price variations on the steam part of a thermal system, by means of a genetic algorithm based optimization programme. They observed that thermodynamic and economic optima for a given fuel price, within the studied range of prices, differ from each other in a quite small percentage over the final cost of the generated energy.

Methodology

Mathematical Modelling: For the present analysis a cogeneration cycle of 30 MW is taken into consideration which is shown figure 1.

In the present system ambient air is entering the compressor and after compression its temperature and pressure is increased. This compressed air is passed through regenerator. In regenerator compressed air is entering from one side and combustion gases coming out of gas turbine from the other. High temperature combustion gases transfer their heat to the compressed air. After gaining heat, compressed air comes to combustion chamber and fuel is added in it. After burning with air, chemical energy of fuel is converted into thermal energy. Temperature of combustion products coming out of combustion chamber depends upon turbine inlet temperature. Combustion product temperature is controlled by making A/F mixture a lean mixture. Gasses coming out from gas turbine are having a large amount of thermal energy. Some part of this thermal energy is transferred to compressed air in regenerator and remaining part is absorbed by high pressure water in steam generator. Flue gas temperature coming out of steam generator is dependent upon the dew point temperature of flue gases. This dew point temperature decides the temperature at which flue gases must enter the stack. For the present analysis air is considered to be a combination of N_2 (77.48%), O_2 (20.59%), CO_2 (.03%) and H_2O (1.9%) and their properties are inbuilt function of software EES. Detailed mathematical modelling may be had from somewhere else.[5] Results obtained are discussed in the following section.

Results and Discussion

For the present analysis air is being considered as a combination of N_2 (77.48%), O_2 (20.59%), CO_2 (.03%) and H_2O (1.9%). The single species are assumed to perform as perfect gases and hence the thermodynamic properties of the species are described depending on temperature only. Species in the liquid or solid phase are not considered in this model. For air the assumption is made, that no chemical reactions take place and hence the species mass fractions are constant, independent of actual pressure and temperature. For combustion gases, a perfect oxidation of the reacting fuel is assumed, resulting in all carbon to form CO_2 and all hydrogen to form H_2O. Therefore with this model no allowance is made for chemical reactions different from those resulting in CO_2 and H_2O, excluding dissociation or recombination. Thus for a given fuel gas ratio, the mass fractions of the single species are constant too. The fuel gas ratio resulting in all the oxygen of the air to be used for the reaction with no excess fuel is named the stoichiometric fuel gas ratio. Fuel gas ratios exceeding the stoichiometric value are excluded in this model, as for those conditions and hydrocarbon fuel a considerable amount of CO is formed and the portion of CO, CO_2 and H_2O varies depending on the variables of state, what cannot be covered with this model.

To take into account imperfect combustion expressed by combustion efficiency less than unity, following a common procedure for the reaction only the fuel fraction given by the efficiency can be used and the remaining fuel can be assumed to have the same properties as air. Regarding the normally small fraction of unburnt fuel this assumption causes a negligible error only. After combustion concentration of N_2, O_2, CO_2 and H_2O is changed. The concentration of different constituents affects the enthalpy of combustion products. Results obtained are shown in the table 1.

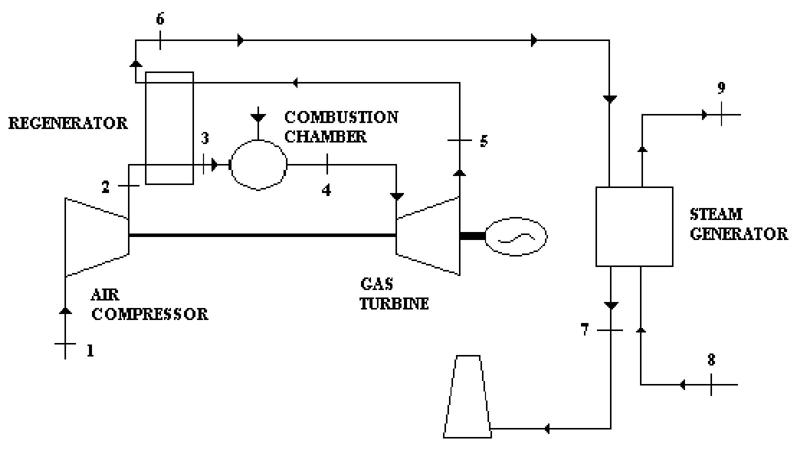

Figure-1
Gas turbine cycle with regenerator

Table-1
Combustion product concentration with and without regenerator

Constituents	Concentration of constituents in inlet air (%)	Combustion product concentration with regenerator (%)	Combustion product concentration without regenerator (%)	Specific heat at constant pressure (kJ/kgK)
Nitrogen N_2	77.48	75.06	74.38	1.12
Oxygen O_2	20.59	13.69	11.76	1.05
Carbon-di-Oxide CO_2	0.03	3.16	4.03	1.16
H_2O	1.9	8.09	9.83	4.19

From the result it is being observed that if regenerator is being used in the gas turbine cycle then the concentration of N_2 and O_2 is 0.91% and 1.41% higher respectively than that of GT cycle without regenerator. The concentration of CO_2 and H_2O is 2.17% and 17.64% lesser respectively for GT cycle with regenerator than that of GT cycle without regenerator. As the fuel is the combination of the carbon and hydrogen, after burning in the oxygen it generates heat energy, CO_2 and H_2O. That is why concentration of H_2O and CO_2 is higher in combustion products than ambient air. Free oxygen is consumed by carbon and hydrogen due to which oxygen concentration decreases.

Another interesting results show that enthalpy of combustion products at a temperature of 155°C is -28077 kJ/kmol for GT cycle with regenerator and for without regenerator enthalpy is -28027 kJ/kmol at a temperature of 389°C. From the results it may be concluded that regeneration not only increases the efficiency of GT cycle but generates a concentration of N_2, O_2, CO_2 and H_2O in such a manner that enthalpy of combustion gas is increased. Regenerator lowers the exergy destruction in the cycle and increased the fuel utilization efficiency for the cycle.

In the present analysis firstly AIT is changed while keeping cycle pressure ratio same. In that case exergy destruction across the compressor and turbine remain same. Exergy destruction in combustion chamber is higher for the cycle without regenerator than with regenerator (figure 2). After compression air comes out at higher temperature and pressure. If regenerator is used in the cycle then temperature of air entering the combustion chamber will be higher than that of without regenerator. Due to which lesser amount of fuel has to be injected in combustion chamber to achieve TIT. It leads to lesser exergy destruction in combustion chamber. For typical atmospheric combustion systems, about 1/3rd of the fuel energy is discharged into the environment as heat. Most of irreversibility within the combustor is due to internal heat transfer between the products and reactants. Such heat transfer becomes inevitable in both premixed and diffusion flames, where highly energetic product molecules are free to exchange energy with unreacted fuel and air molecules.[6]

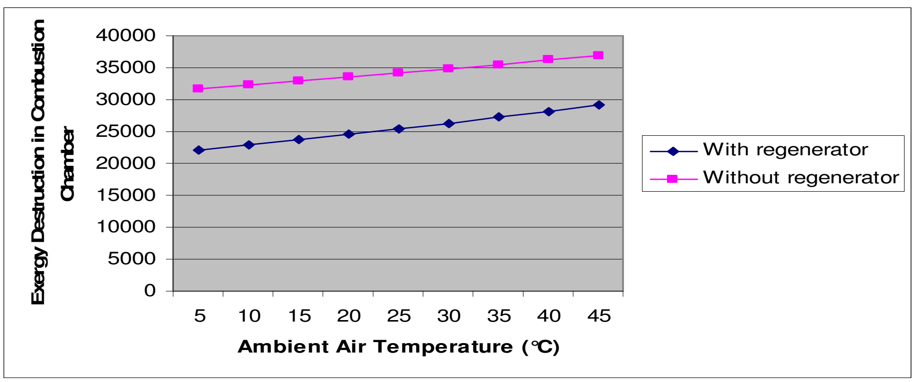

Figure-2
Exergy destruction in combustion chamber with change in ambient air temperature for the cycle with regenerator and without regenerator

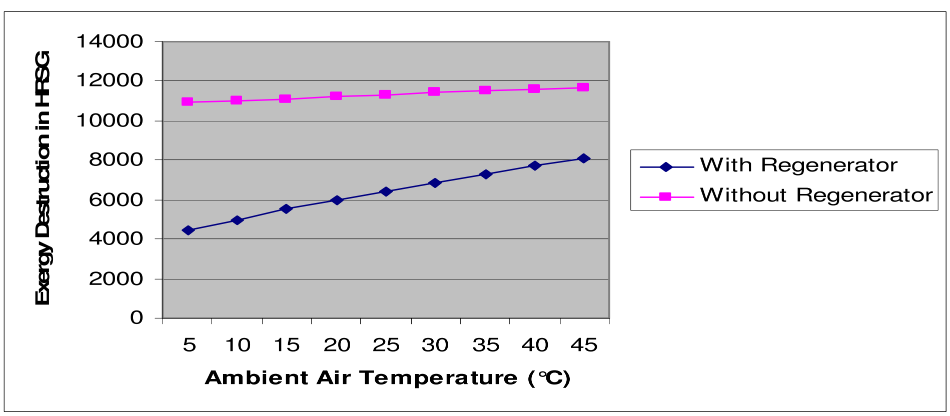

Figure-3
Exergy destruction in HRSG with change in ambient air temperature for the cycle with regenerator and without regenerator

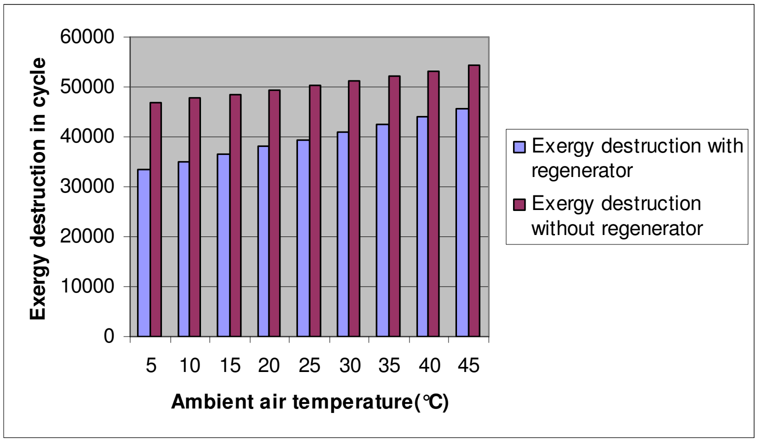

Figure-4
Change in exergy destruction in cycle with and without regenerator for change in ambient air temperature

In the present analysis regenerator is installed before HRSG. Exergy destruction in HRSG is associated with friction losses and temperature difference in the fluids passing through it. In the gas turbine cycle with regenerator, temperature of flue gases is lowered by regenerator before entering HRSG. As the temperature difference between flue gases and water becomes low, exergy destruction is decreased in regenerator. If regenerator is not used, then flue gases coming out of gas turbine at relatively higher temperature causes higher exergy destruction in HRSG. Regenerator lowers the overall exergy destruction in the cycle (figure 4). Although exergy destruction takes place in regenerator but it is less than the exergy destruction saved by regenerator in combustion chamber and HRSG.

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