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Thermodynamic analysis of a regenerative gas turbine cogeneration plant

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Design methodology has been developed for parametric study and thermodynamic performance evaluation of a gas turbine cogeneration system (GTCS). Parametric study showed that compression ratio (r_p), inlet air temperature, turbine inlet temperature, steam pressure and pinch point temperature played a very vital role on overall performance of GTCS. Exergy analysis revealed that most sensitive components in GTCS were combustion chamber and regenerator.

Keywords: Gas turbine cogeneration plant, Parametric study, Thermodynamic analysis

Introduction

Gas turbine designs have been successfully used for cogeneration. Gas turbine cogeneration system (GTCS) requires improvement in thermodynamic performance with reduced expenditure. Moran[1] developed analysis methodology for GTCS. Khaliq & Kaushik[2] studied efficiency of GTCS with heat recovery steam generator (HRSG). Doek *et al*[3] worked out exergy analysis and calculated performance of GTCS as well as exergy destruction in each component in GTCS. Butcher & Reddy[4] analyzed second law efficiency of waste heat recovery and studied effect of pinch point temperature on efficiency of HRSG. Korakianitis[5] performed analysis of combined GTCS with various power and efficiency enhancement techniques. A conceptual gas turbine based cogeneration cycle[6] with compressor inlet air cooling and evaporative after-cooling of discharge has been proposed. Yokoyana *et al*[7] worked on optimal design of GTCS in consideration of discreetness of equipment capabilities. Dellenback[8] reassessed an alternative regenerative cycle. Ali[9] studied simple gas turbine system with inlet air refrigeration by vapour compression cycle. Kumar & Krishna[10,11] performed second law analysis of gas turbine power plant with alternative regeneration.

This study presents combined application of first and second law analysis for performance analysis of GTCS considering pressure ratio, turbine inlet temperature (TIT), pressure drop etc.

Experimental

Gas turbine cogeneration system (GTCS)

A standard GTCS (Fig. 1) consists of a closed Brayton cycle with $CH_4 – O_2$ combustion and a HRSG utilizing waste heat of the cycle, which is comprised of an air compressor, regenerator, combustor and a turbine. Air after compression in compressor enters regenerator where its temperature is raised by exhaust gases from turbine. Air then enters into combustion chamber where its temperature is raised by combustion of fuel. Gases then expand in turbine and produce work output (alternator to generate electricity). Heat carried by exhaust gases is recovered in regenerator and HRSG to increase temperature of air and generate process steam respectively.

Thermodynamic Formulation

Mathematical formulation of present analysis is based on following assumptions: i) Cogeneration system operates at steady state; ii) Ideal gas mixture principles apply for air and combustion products; iii) Fuel (natural gas) is taken as methane and modeled as an ideal gas; iv) Combustion in combustion chamber is complete and N_2 is treated as inert; v) Heat transfer from combustion chamber is 2% of lower heating value (LHV) of fuel; and vi) All other components operate without heat loss. A computer program was developed to simulate GTCS, in which control volume analysis of each component

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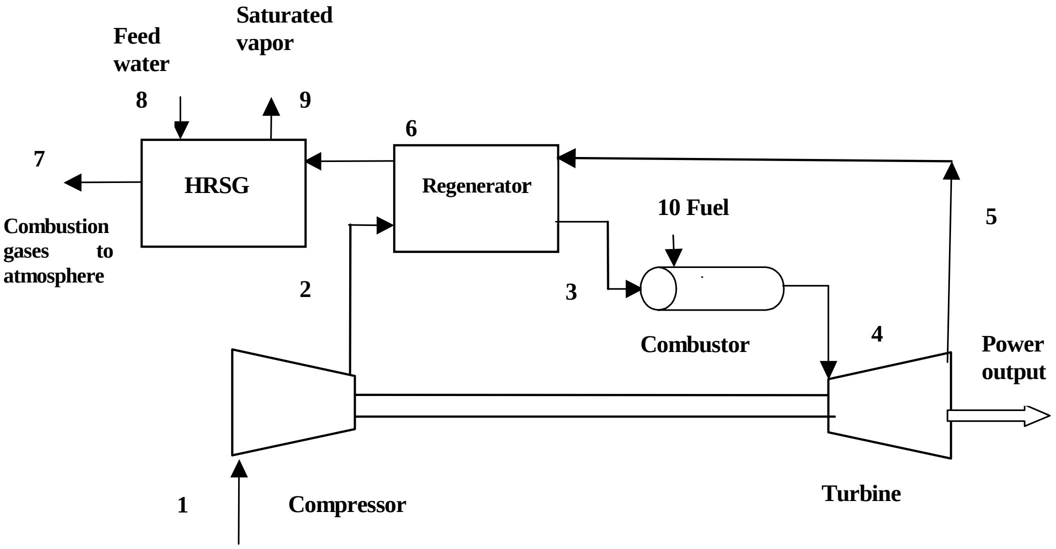

Fig. 1—Gas turbine cogeneration system with regeneration

was performed using mass, energy and exergy balances for determining thermodynamic properties at every key position (Fig. 1). Parameters required for combined first and second law analysis of GTCS may be taken as

First – Law Efficiency (η_I)

Ratio of all useful energy extracted from system (electricity and process heat) to energy of fuel input is first-law efficiency, given as

$$\eta_I = \frac{W_g - Q_p}{H_F} \qquad \ldots(1)$$

where, W_g, Q_p and H_F represent power output, process heat and heat input respectively.

Second-Law Efficiency (η_{II})

Since exergy is more valuable than energy according to second law of thermodynamics, it is useful to consider both output and input in terms of exergy, defined as

$$\eta_{II} = \frac{W_g + (E_9 - E_8)}{(E_{10} + E_1)} \qquad \ldots(2)$$

Power-to-Heat Ratio (R_{PH})

R_{PH} is defined as

$$R_{PH} = \frac{W_g}{Q_p} \qquad \ldots(3)$$

Results and Discussion

Effect of pressure ratio (r_p) across compressor, TIT, ambient temperature and relative humidity (φ) on η_I and R_{PH} is obtained by energy balance approach or first law analysis of cycle. However, exergy destruction or thermodynamic losses of each component and η_{II} of cycle has also been investigated under exergy balance approach or second-law analysis of cycle.

Input Conditions

In order to study effect of operating variables on performance parameter of the system, operating under different conditions, common characteristics and their corresponding ranges were chosen. In present simulation, parameters were varied as follows: inlet air temperature, 0-50°C; r_p, 5-50; and TIT, 1300-1900 K. Reference values for ambient temperature and pressure of air were taken as 298.15 K and 1.013 bar respectively at relative humidity (60%). Effectiveness of regenerator has been taken as 0.8. System component efficiencies were as follows: compressor isentropic efficiency η_c, 87%; turbine isentropic efficiency $\eta_{r,}$ 89%; efficiency of combustion chamber and reheater (η_{CC} and η_{regen}), 95%; and generator efficiency (η_g), 97%. Pinch point temperature *(η_{pp})* at HRSG was taken as 25°C and varied (0-50°C). Temperature of condensate return from process

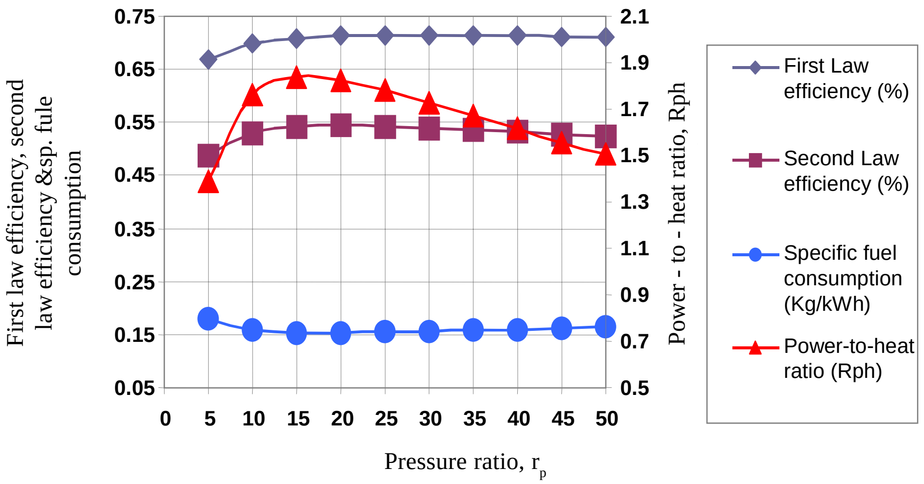

Fig. 2—Variation of Ist and 2nd law efficiency, specific fuel consumption and power-to-heat ratio with pressure ratio

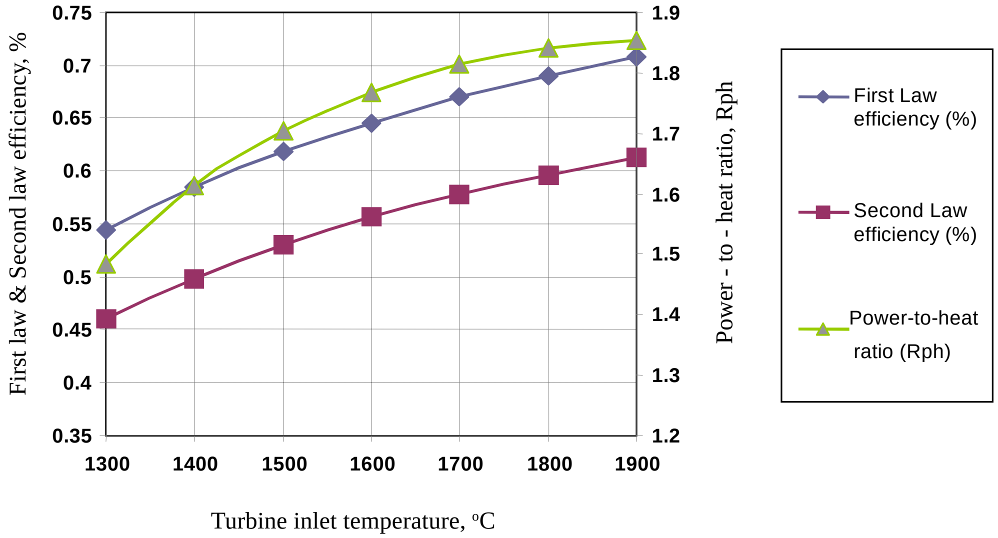

Fig. 3—Effect of variation of turbine inlet temperature on first law efficiency, second law efficiency and power-to-heat ratio

was taken as 25°C (open circuit). Process steam pressure was taken as 10-20 bar. Methane (CH_4) gas (mol wt, 16.043 g/mol) was taken as fuel (LHV, 802361 kJ/ kmol).

Effect of Pressure Ratio (r_p)

Variation in η_I, η_{II}, R_{PH} and specific fuel consumption (SFC), for GTCS with compressor r_p for TIT at 1900 K, indicated (Fig. 2) that as r_p increases, compressor work increases, raising temperature of air at compressor outlet. Increase in r_p also increases turbine work and net work output of the cycle. Therefore, as r_p increases, air temperature at inlet of regenerator increases and reduces heat transfer capacity (from combustion products to hot air) of regenerator, causing increase in gas temperature at exit of regenerator and thus increase in energy available to generate process heat. Thus optimum pressure ratio is 20, for which first and second law efficiency is maximum and SFC is minimum. R_{ph} increases up to optimum r_p and afterwards it decreases with increase in r_p.

Effect of Turbine Inlet Temperature (TIT)

Variation in η_I, η_{II}, R_{PH} with change in turbine inlet temperature for r_p=20, cycle efficiency increases with an increase in TIT (Fig. 3). Similarly, R_{PH} increases appreciably as TIT increases.

Effect of Compressor Inlet Air Temperature

Looking into impact of compressor inlet air condition (0-50°C) on η_I, η_{II}, and R_{PH} at TIT =1900 K

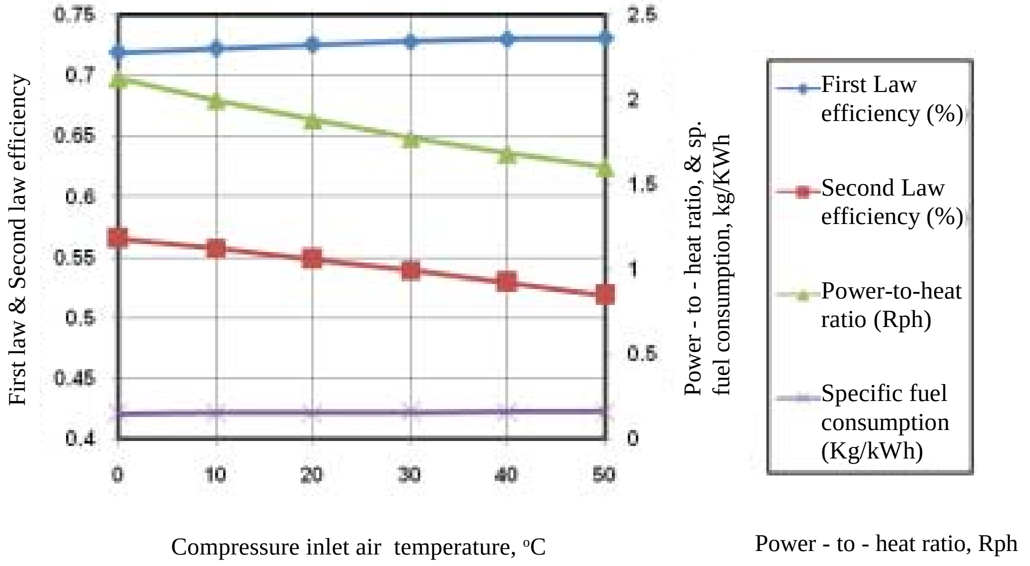

Fig. 4—Ist law efficiency, 2nd law efficiency, power-to-heat ratio and specific fuel consumption at different ambient temperatures

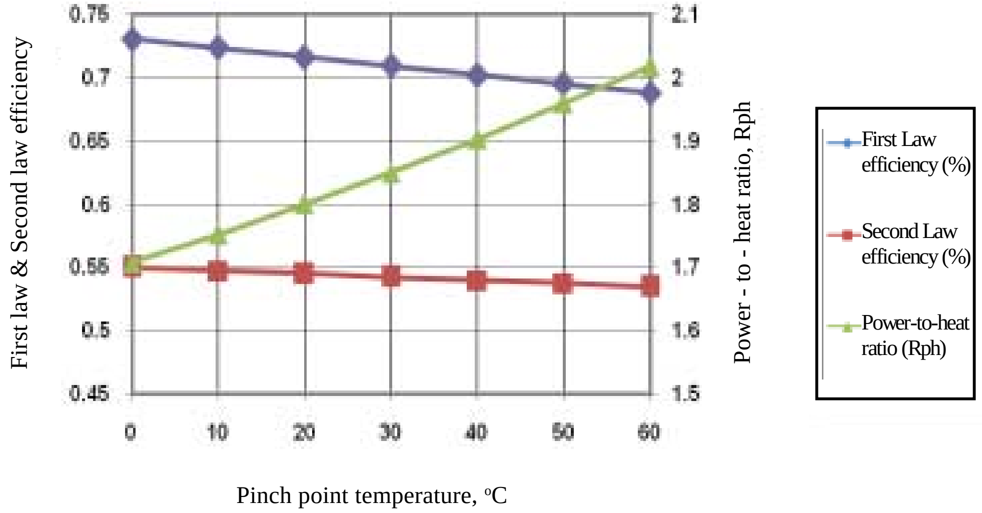

Fig. 5— Effect of pinch point temperature on first and second law efficiency and power - to- heat ratio of gas turbine cogeneration system [saturated steam pressure = 20 bar]

and r_p= 20 (Fig. 4), η_I and SFC slightly increase with inlet air temperature. Increase in inlet temperature shows significant effect on η_{II}, due to which GTCS shows a relatively inferior performance in summer as compared to winter. Therefore, now- a-days various techniques for cooling of inlet air to compressor is employed.

Effect of Pinch Point And Process Steam Pressure

Variation of pinch point on system performance with fixed process steam pressure indicated (Fig. 5) that η_I and η_{II} (exergetic) decrease and R_{PH} increases with an increase in pinch point. Further, R_{PH} slightly increases with increasing process steam pressure (Fig. 6). It is advisable raising steam pressure above thermodynamic equilibrium, because it causes a reduction in exhaust steam flow for a given power output, thus reducing size of condenser and cooling water requirement.

Exergy Destruction

Variation of exergy destruction in each component of plant with change in overall r_p from 10 to 50 for TIT = 1900 K indicated (Fig. 7) that exergy destruction in

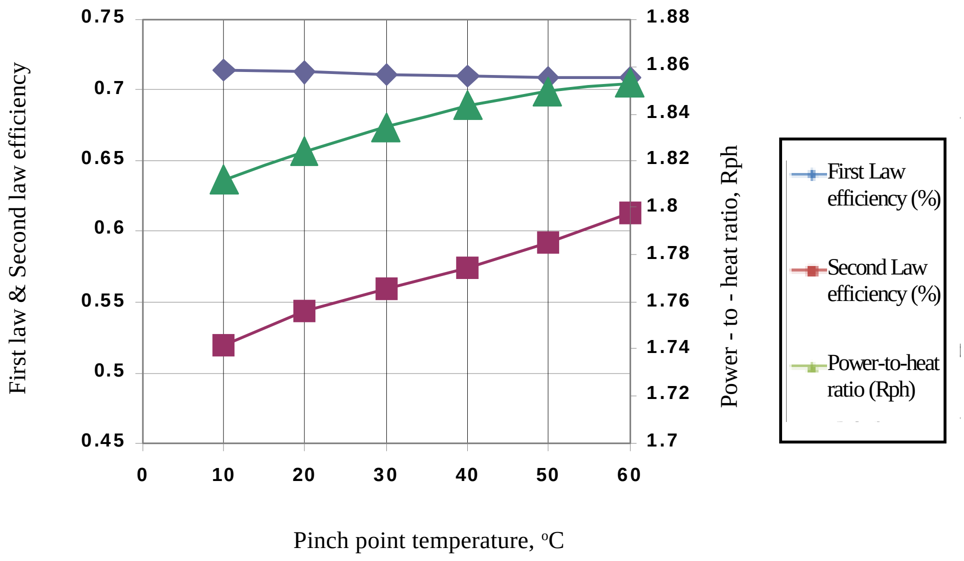

Fig. 6—Effect of variation of steam pressure in HRSG on first law efficiency, second law efficiency, and power-to-heat ratio

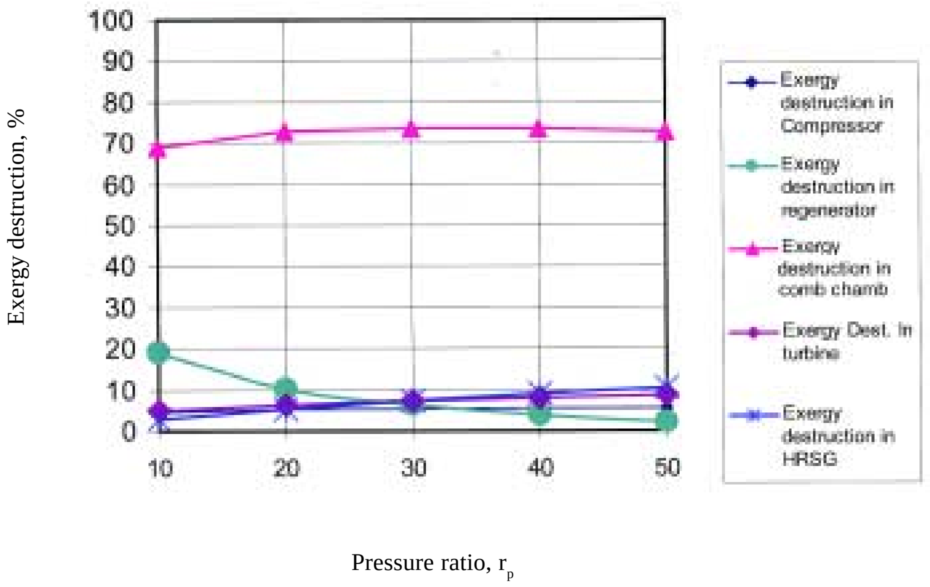

Fig. 7—Effect of variation of pressure ratio on exergy destruction in different components of cycle for TIT = 1900 K, φ = 60%, ρ_1 = 1.013 bar, T_1 = 298.15 K

combustion process dominated exergy destruction picture. It represented over 69-73% of total exergy destruction in overall system for entire range of r_p. As r_p increased (10-20), exergy destruction in combustion chamber increased significantly. Variation of magnitude of exergy destruction in each component of plant with change in turbine inlet temperature for r_p=20 indicated (Fig. 8) that as TIT increases, exergy destruction in regenerative heat exchanger increases. Variation of exergy destructions in each component of plant with ambient temperature (5-45°C) for TIT = 1900 K and r_p = 20 indicated (Fig. 9) that exergy destruction in combustion process dominates exergy destruction picture.

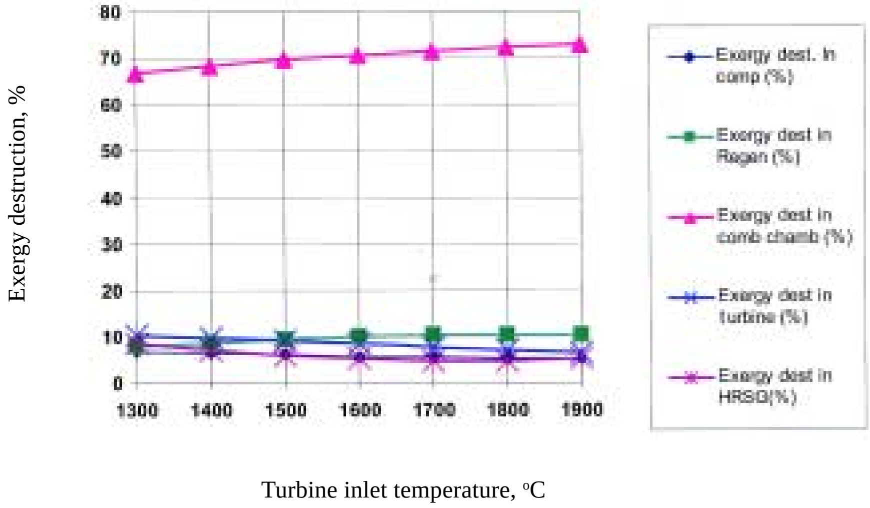

Fig. 8—Effect of variation of TIT on percentage exergy destruction in different components of cycle for $r_p = 20$, $\varphi = 60\%$, $\pi_1 = 1.013$ bar, $T_1 = 298.15$ K

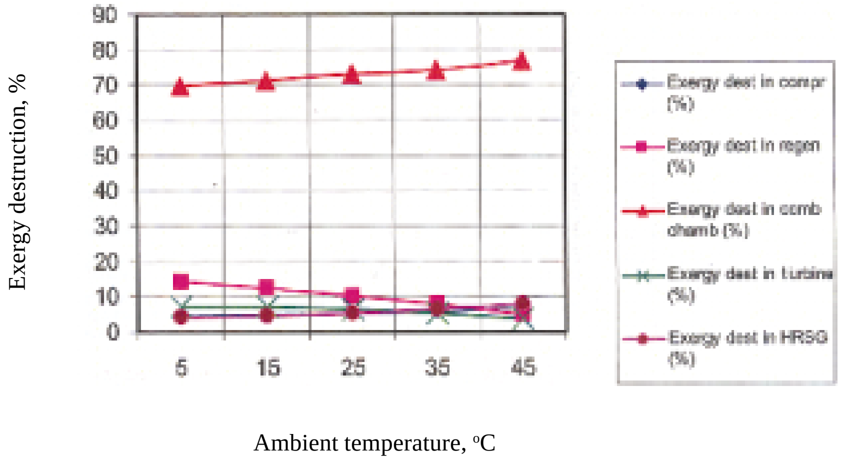

Fig. 9—Effect of variation of ambient temperature (inlet air) on exergy destruction in different components of cycle for r_p= 20, p_1= 1.013 bar, T_1= 298.15 K

Conclusions

A design methodology has been developed for parametric study and performance evaluation of a GTCS. Parametric study showed that r_p, inlet air temperature, TIT, steam pressure and pinch point temperature played a very vital role on overall performance of GTCS. Exergy analysis revealed that most sensitive component in GTCS was combustion chamber and regenerator.

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