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Thermodynamic Analysis of Gas Turbine Trigeneration System

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Abstract: Trigeneration can be considered as a special case of the application cogeneration system where a fraction of the shaft work or residual heat is running a refrigeration system. Trigeneration with gas turbines as prime mover can improve energy utilization efficiency significantly because of their potential of high economic and energy saving characteristic. Trigeneration system based on the conventional gas turbine cycle for the high temperature heat addition while adopting the heat recovery steam generator for process heat and vapor absorption refrigeration for the cold production Combined first and second law approach is applied and computational analysis is performed to investigate the effects of overall pressure ratio, turbine inlet temperature, pressure drop in combustor and heat recovery steam generator, and evaporator temperature on the exergy destruction in each component, first law efficiency, electrical to thermal energy ratio, and second law efficiency of the system. The first law efficiency, electrical to thermal energy ratio and second law efficiency of the trigeneration, cogeneration, and gas turbine cycle significantly varies with the change in overall pressure ratio and turbine inlet temperature, but the change in pressure drop, process heat pressure, and evaporator temperature shows small variations in these parameters.

Keywords: Exergy, Heat recovery, Trigeneration

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I. INTRODUCTION

Cogeneration is an engineering concept involving the production of both electricity and useful thermal energy in one operation, thereby utilizing fuel more efficiently than if the desired products were produced separately. The requirements of cogeneration may be met in many ways ranging from steam and gas turbines to fuel cells and Stirling engines. The disadvantage of the abovementioned conventional cogeneration system is that to get high energetic and economic efficiency is subject to such an application where the need for both heat and electric power is balanced throughout the year. There is no balanced need for electricity and heat in most practical applications of conventional cogeneration units. What more, there is a great demand of cooling for technological purposes or air-conditioning in different objects. From the energetic and economic point of view, the most efficient utilization of the primary energy is in such case possible by such cogeneration systems that are able to produce simultaneously power, heat, and also cold with the possibility of output ratios of individual energy flows. These combined energy systems may be named as trigeneration which is a combined production of electricity, heat, and cold. For domestic and industrial applications where various kinds of energy are demanded, this turns out to be a very effective energy saving system. Maidment and Tozer (2002) have reviewed a number of trigeneration plants operating in supermarkets. Bassols et al. (2002) have presented different examples of trigeneration plants in the food industry. All analyzed examples are using an absorption chilling machine for cold production.

Thermodynamic analysis can be a perfect tool for identifying the ways for improving the efficiency of fuel use, and determining the best configuration and equipment size for a trigeneration plant. Athanasovici et al. (2000) have presented a unified comparison method for the calculation of thermodynamic efficiency applied to CHP plants. A comparison between the separate and combined production of energy has been performed using the proposed method. Havelsky (1999) has analyzed the problem of energetic efficiency evaluation of cogeneration system for combined heat, cold and power production. Equations for energetic efficiency and primary energy savings have been presented. Minciuc et al. (2003) presented a method for analyzing trigeneration systems, and established the limits for the best energetic performance of gas turbine trigeneration with absorption chilling machine from thermodynamic point of view. As is seen, most of the studies in the above cited literature have been conducted using the first law of thermodynamics or energy balance approach.

II. METHODOLOGY

Fig. 1 shows the schematic diagram of trigeneration system. In this system, Ambient air is compressed from state 1 to state 2 and is then supplied to the combustion chamber (CC) where fuel is burned, producing hot gas at 3. The hot gas is then expanded to 4 in turbine (T) to a lower pressure and temperature. This expanded gas is utilized in the HRSG to generate process heat $\dot{Q}_P$the stack gas coming out of HRSG (at 5) is sent to the generator of vapor absorption system. The refrigerant H_2O is separated from LiBr/H_2O in the generator by means of the heat given by the stack gas. The solution circulation ratio depends on the temperature to which the solution is heated. After refrigerant has reached the desired temperature it goes through the condenser at 6 and the evaporator at 8 through the expansion valve at 7. The water vapor mixture that enters the evaporator at 8 is boiled and exits the evaporator in a saturated state at 9. The saturated steam at 9enters the absorber where it mixes with a weak solution at 15, generating heat that has to be dissipated to increase the efficiency of mixing process. The heat released in the condenser and in absorber is rejected to the cooling water. The mixing process results in a strong solution that exits the absorber at 10 and is pumped to the upper pressure of the cycle at 11. The high pressure strong solution at 11 is heated to a higher temperature at 12 in the heat exchanger (HE) using the counter pass, high pressure, weak solution at 13. The cooler weak solution exits the heat exchanger (HE) at 14 and is expanded in the throttling valve (TV), resulting in a low pressure, and weak solution at 15.

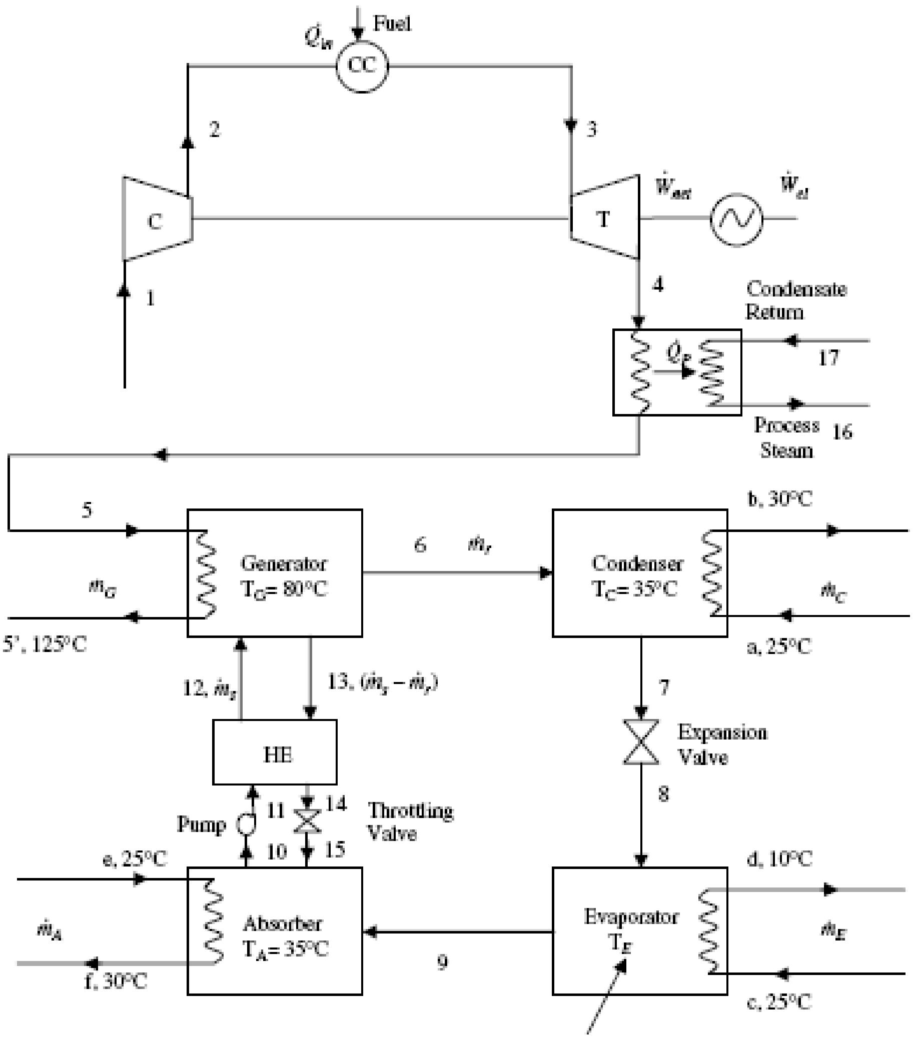

Fig 1. Diagram of the gas turbine trigeneration system for combined heat cold and power production

2.1 Thermodynamic Analysis:

(a) Power Output:

The net power output of a cycle is given by,

$\dot{w}_{net}$ = $(\dot{m}_a + \dot{m}_f)\,(h_3 - h_4)$ - $\dot{m}_a(h_2\text{-}h_1)$ (1)

Assuming air to be an ideal gas with constant specific heats, Eq. (1) may be written as

$\dot{w}_{net}$ = $(\dot{m}_a+\dot{m}_f)c_p\,(t_3\text{-}t_4)\text{-}\dot{m}_a c_p(t_2\text{-}t_1)$ (2)

The specific net power output of the cycle is,

$w_{net} = \dot{w}_{net} / \dot{m}_a c_p T_1$

= (1+A) θ and $\pi_T \psi_T \text{-} \frac{(\psi_C)}{(\eta_c)}$

Where θ =$\frac{T_3}{T_1}$, A= $(\frac{\dot{m}_f}{\dot{m}_a})$

The electrical power output of the system is given by

$\dot{W}_{el} = \eta_g \dot{w}_{net}$ (3)

Where η_g is the mechanical to electrical conversion efficiency.

(b) Energy Input:

The total heat input to the cycle is given by

$\dot{Q}_{in}$= $\dot{m}_a[(1\text{+A})h_3\text{-}h_2]$

= $\dot{m}_a c_p[(1\text{+A})\ T_3\text{-}T_2]$

Where A is the fuel to air ratio

Energy of fuel input$\dot{Q}_f$, may be obtained from,

$\dot{Q}_f$ =$\frac{\dot{Q}_{in}}{\eta_{cc}}$

Where η_{cc} is the combustion chamber efficiency.

(c) Process Heat Production:

The amount of process heat rate $\dot{Q}_p$ produced is given by,

$\dot{Q}_p$= $(\dot{m}_a+\dot{m}_f)\ (h_4\text{-}h_5)$

(d) Refrigeration or Cold Production:

The amount of cold produced ($\dot{Q}_E$) may be obtained after applying the energy balance on evaporator as:

$\dot{Q}_E$=$\dot{m}_r(h_9\text{-}h_8)$

$\dot{E}_E$ = $\dot{Q}_E(\frac{T_0 - T_E}{T_E})$

(e) Electrical to Thermal Energy Ratio:

R_{ET} = $(\frac{\dot{W}_{el}}{\dot{Q}_P+\dot{Q}_E})$

R_{ET} = electrical to thermal energy ratio

III. RESULT AND ANALYSIS

In the present work the effects of pressure ratio across the compressor (π_c), turbine Inlet temperature (TIT), percentage pressure drop (%) on electrical to thermal energy ratio (RET) is obtained by energy balance approach or the first law analysis of the cycle.
The following graph shows the variation of different parameters over electrical to thermal energy ratio.

3.1. Compressor pressure ratio versus Electrical to thermal energy ratio

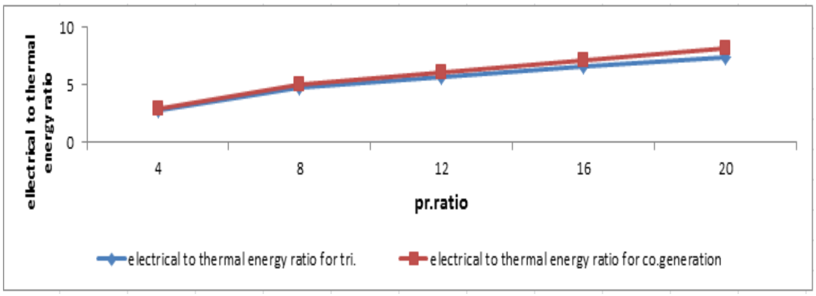

Fig 2. Effect of Variation of Pressure ratio on Electrical to Thermal Energy ratio

3.2. T.I.T versus Electrical to thermal energy ratio

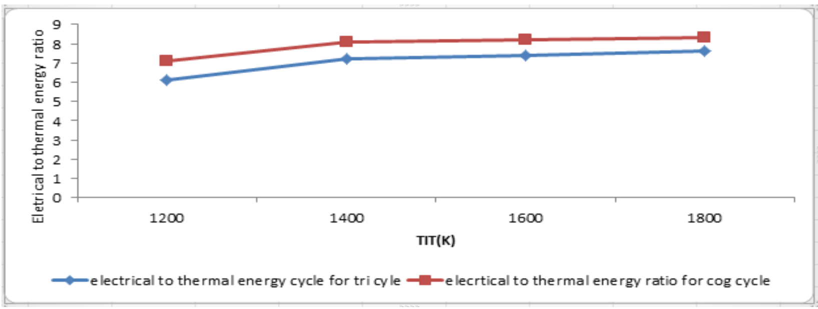

Fig 3. Effect of Variation of Turbine inlet Temperature on electrical to thermal energy ratio

3.3. T.I.T versus Electrical to thermal energy ratio

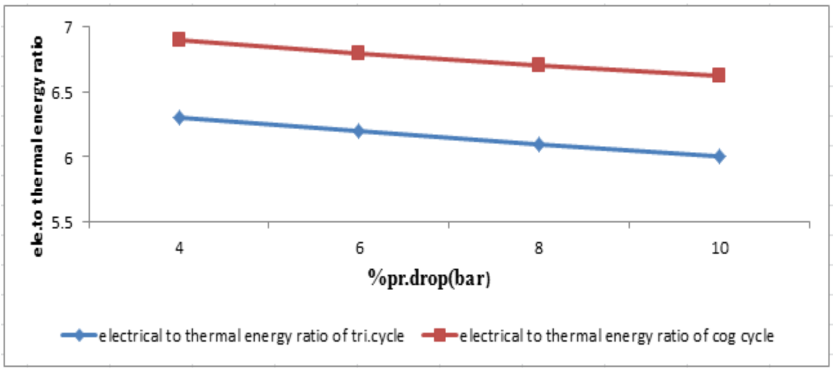

Fig 4. Effect of Variation of % Pressure drop on Electrical to Thermal Energy Ratio

IV. DISCUSSION

As the pressure ratio (π_c) increases the compressor work increases, raising the temperature at compressor outlet. Increase in pressure ratio also increases the turbine work. The network output first increases and then decreases as at high pressure ratio compressor work increases rapidly. As the pressure ratio increases the air temperature at the inlet of combustion chamber increases which results in decreasing the heat added to the cycle. Hence, as π_c increases, the first law efficiency of the gas turbine cycle increases. The second law efficiency is slightly lower than the first law efficiency of the gas turbine cycle. The first law efficiency of cogeneration cycle is higher than first law efficiency of gas turbine cycle because the gas turbine exhaust is utilized to produce the process heat. The second law efficiency for cogeneration cycle is higher than the second law efficiency for gas turbine cycle but the difference between the second Law efficiency for cogeneration cycle and gas turbine cycle is less as compared to the difference between the first law efficiency of both. decreases when the pressure drop increases.

V. CONCLUSION

The exergy-balance equation, which is applicable to any thermal system, has been applied to the trigeneration cycle for combined production of power, heat and refrigeration. From thermodynamic point of view, the combination of gas turbine with absorption chilling machine in these trigeneration systems proves to be highly efficient.

[1]. The first law efficiency, electrical to thermal energy ratio, and second law efficiency of gas turbine, cogeneration and trigeneration cycles are not at all affected with the pressure drop in combustion chamber and HRSG.

[2]. Maximum exergy is destroyed during the combustion and steam generation process; it represents over 80% of the total exergy destruction in the overall system.

[3]. The exergy destruction in combustion chamber and heat recovery steam generator decreases significantly with the increase in pressure ratio but increases significantly with the increase in turbine inlet temperature.

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