Thermodynamic analysis of steam-injected advanced gas turbine cycles

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Abstract. This paper deals with thermodynamic analysis of steam-injected gas turbine (STIGT) cycle. To analyse the thermodynamic performance of steam-injected gas turbine (STIGT) cycles, a methodology based on pinch analysis is proposed. This graphical methodology is a systematic approach proposed for a selection of gas turbine with steam injection. The developed graphs are useful for selection of steam-injected gas turbine (STIGT) for optimal operation of it and helps designer to take appropriate decision. The selection of steam-injected gas turbine (STIGT) cycle can be done either at minimum steam ratio (ratio of mass flow rate of steam to air) with maximum efficiency or at maximum steam ratio with maximum net work conditions based on the objective of plants designer. Operating the steam injection based advanced gas turbine plant at minimum steam ratio improves efficiency, resulting in reduction of pollution caused by the emission of flue gases. On the other hand, operating plant at maximum steam ratio can result in maximum work output and hence higher available power.

1. Introduction

The biggest challenges of today are the environmental concern due to pollution mainly flue gases, depletion of fossil fuel reserves and fluctuating prices of fuels. These challenges have motivated researchers to find new energy sources on one side and to improve existing plant efficiency on another. Gas turbine power plant mainly uses natural gas having more clean combustion but with reduced efficiency. To get the advantage of clean combustion, researchers tried to improve its efficiency by modifying basic cycle operation. Out of various advanced gas turbine cycles, in STIGT cycle, steam is formed from water by recovering heat available in exhaust of gas turbine. This heat is injected in to combustion chamber in the form of saturated or superheated steam, further improving the gas turbine cycle efficiency. This will definitely helpful for cost feasibility, if it is designed at optimal condition. Improved efficiency of STIGT will reduce pollution due to flue gas decreasing global warming effects.

A lots of work carried out on cogeneration plants [1] [2,3] [4] [5], combined cycle plants [6–10] and advanced gas turbine cycle [11] [11–13] to improve the cycle efficiency for various operating conditions. Burnham et al. [14] performed full scale test of a steam injection system and analyzed economics of plant. Foster-pegg [15] had compared turbo-charged STIGT with cogeneration plant and indicated more suitability of first one. Bolland, and Stadaas [16] evaluated water, steam and recuperative gas turbine cycle performance and compared with combined cycle. Heppenstall [2] critically reviewed advanced gas turbine cycles indicating combined cycle will be preferred for new plants. Najjar [1] had reviewed work carried by his team regarding the advanced gas turbine cycles. Horlock [17] in his book described most of the aspects of gas turbine power plant with advanced
cycles. Further reduction of pollution, researchers tried to integrate gas turbine with other energy sources such as solar dish micro combined cycle [18], CO₂ capture [19,20] etc. Bade and Bandyopadhyay [21] had proposed methodology to select efficient cogeneration system based on novel graphs pressure ratio versus R curve (heat to work ratio) at maximum performance indicators. This is useful for both new as well as retrofitted plants. Fabenle et al. [22] analyzed biogas-fired integrated gasification STIGT plant based on exergy criteria. Primary objective of this paper is to propose a methodology for appropriate integration of advanced gas turbine cycle so that overall fuel consumption is reduced.

2. Steam-injected gas turbine (STIGT)

Figure 1 presents the schematic of STIGT plant with details of operation of it. Inlet air of mass flow rate \( m_a \) (at ambient temperature, \( T_a \) and pressure, \( P_a \)) is compressed until pressure \( P_{aco} \) (with a corresponding temperature of \( T_{aco} \)) is reached. Then, steam \( (m_i) \) is heated in regenerator up to temperature \( T_{sicc} \) using exhaust flue gas mixture from turbine gas. Subsequently, preheated steam \( (T_{sicc}) \) and compressed air \( (T_{aco}) \) are injected in to combustion chamber where fuel of mass flow rate \( m_f \) is burnt. The product of combustion termed as flue gas mixture (mass flow rate, \( m_g + m_s \)) at a specified maximum temperature \( (T_{gfl}) \) is expanded in gas turbine to generate net work \( W_{net} \). The flue gas at gas turbine exit temperature \( (T_{gfl}) \) is supplying heat to covert water into steam. This steam is subsequently supplied to combustion chamber. Maximum ratio of mass flow rate of steam to air is accounted such that water is heated up to saturated steam condition and heat required per unit mass of air in flue gas is always greater than this required heat duty \( Q_{steam} \).

![Figure 1: Layout of Gas turbine with steam injection](image)

3. Problem definition

For a given gas turbine plant, water or steam heating requirement is known. The design data of gas turbine such as ambient air temperature \( (T_a) \) and pressure \( (P_a) \), gas turbine temperature at inlet to turbine \( (T_{gfl}) \), specific heats of air and flue gas, water and steam enthalmies at required conditions, etc. are given. The minimum temperature difference between water-steam and flue gas mixture is considered 50 K. The STIGT plant supplies heat available in flue gas mixture at gas turbine exhaust to satisfy required heat duty to convert water into steam \( Q_{steam} \). It is assumed that the heat available in the exhaust flue gas is always greater than or equal to the required heat duty to convert water into saturated steam \( Q_{steam} \). This is accomplished by maintaining appropriate steam ratio \( S_o \) (ratio of mass flow rate of steam to air). The objective is to develop a methodology for optimal performance of the advanced gas turbine cycle for maximum efficiency or power output.

4. Thermodynamics analysis of STIGT

An analytical methodology for energy integration of gas turbine and steam heating, together carried out in steam injected gas turbine (STIGT) plant is developed in this section. Methodology proposed by Bade and Bandyopadhyay [21] for energy integration of gas turbine with overall process is appropriately modified to apply for STIGT for various criteria.
The heat available in flue gas mixture (gas and steam) at the outlet of gas turbine utilized to convert water into steam. The analysis is carried out per unit mass of air and important parameter considered are ratio of mass flow rate of steam to air \((S_r = m_s/m_a)\) and pressure ratio of turbine cycle. Consider the gas turbine cycle plant without injection of steam \((S_r=0)\). By using simple analysis, efficiency can be determined. If small amount of steam per kg of air is added by heating it using flue gas mixture, total mass of flue gas mixture will increase by additional steam amount. In effect, partially, extra heat energy needs to be supplied with surplus work output from gas turbine. Energy required for heating water can be presented in the form of grand composite curve (GCC) called as steam GCC [21]. A steam ratio, \(S_r\) can be targeted graphically by matching flue gas mixture line drawn from temperature of flue gas mixture at gas turbine exit with steam GCC [21], as shown in Figure 2. The ratio of mass flow rate of flue gas to steam is given by following equation:

\[
\frac{m_y}{m_z} = \frac{(q_{steam} - h_k) - (h_{steam} - h_k)}{C_{pg}(T_{gas} - T_k)}
\]  

(1)

where, \(q_t\) and \(T_k\) are coordinates of one of the vertexes of steam GCC with additional stack temperature and \(C_{pg}\) is specific heat capacity at constant pressure of flue gas, \(h\) represent enthalpy of steam at respective temperatures. The maximum among the flue gas flow rate determined at each vertex is the minimal flow rate of flue gas for which complete process heat demand is satisfied. At this condition, steam is at saturated condition. The point at which flue gas line just touches process GCC or stack temperature is known as utility pinch (point 5 in Figure 2) and temperature at that point termed as utility pinch temperature \((T_k)\). Overall mass balance is written as:

\[
m_a + m_f + m_s = m_g + m_s
\]  

(2)

Figure 2. Targeting of \(S_r\) by matching steam heating

The compressed air (at temperature, \(T_{cco}, m_a\)) and steam are used for burning fuel in the combustion chamber. The flue gas temperature at exit of combustion chamber is \(T_{gco}\). The energy balance for combustion chamber is given as:

\[
m_sC_{ps}(T_{cco} - T_a) + m_s(h_{gcc}) + CV \cdot \eta_{cc}m_f = m_pC_{pg}(T_{gco} - T_a) + m_f(h_{gco})
\]  

(3)

where, \(CV\) is net calorific value of fuel, \(\eta_{cc}\) is combustion efficiency and \(C_{ps}\) is specific heat capacity at constant pressure of air.

Pinch analysis may be applied to determine steam ratio, \(S_r\) for various conditions of integration. Figure 3 illustrates the heat duty available (temperature of flue gas from gas turbine exit, \(T_{gto}\) to stack, \(T_{st}\)) and heating required (temperature of water-steam from ambient temperature to maximum combustion chamber inlet temperature) by composite curves. The maximum superheat steam temperature possible is flue gas exhaust temperature with minimum approach temperature i.e. \((T_{gto} - \Delta T)\). Similar to GCC in pinch analysis, the GCC for flue gas mixture is a plot of enthalpy difference between utility composites as shown in Figure 3. It should be noted that the GCC for flue gas mixture is shown as reflected (see Figure 2 and 3). This helps in matching it with GCC of steam to balance utility requirement as shown in Figure 3. The matched GCC of flue gas mixture and GCC of steam,
pinch point, stack losses, etc. are shown in Figure 3. All GCCs are plotted on shifted temperature scale with minimum approach temperature, $\Delta T$. Heat lost by flue gas mixture is equal to heat received by water required to convert it into steam for minimum approach temperature. This energy balance equation can be written to get minimum $S_i$ as:

$$\frac{m_i}{\eta_i} = \frac{[q_i(T_{gi} + \Delta T) - q_i] - (b_{gi} - b_{hc})}{c_{pg}(\frac{T_{gi} + \Delta T}{2} - T_{gi})}$$ (4)

where, $q_i(T_{gi} + \Delta T)$ is enthalpy of steam inlet to combustion chamber at $(T_{gi} + \Delta T)$. The minimum ratio of mass flow rate of steam to air is determined at optimal integration using Equations 2, 3, and 4 appropriately as follows:

$$S_i = \frac{m_i}{\eta_i} = \frac{[q_i(T_{gi} + \Delta T) - q_i] - (b_{gi} - b_{hc})}{c_{pg}(\frac{T_{gi} + \Delta T}{2} - T_{gi})}$$ (5)

where, $q_i$ and $T_{gi}$ are the coordinates of one of the vertexes of steam GCC with additional of stack temperature. $q_i$ is total heat required for steam heating per unit mass of air and equals to the enthalpy of the superheat steam at gas turbine outlet temperature with minimum approach temperature. However, the pinch points are not known a priori. Since pinch is going to form at one of the vertexes of GCC of steam including stack temperature, steam rate ($S_i$) can be calculated following Equation 5, for each vertex ($i = 1, \ldots, k$). The maximum of steam ratio ($S_i$) calculated for each vertex including stack temperature represents the minimum steam ratio, $S_i$ for optimal integration of STIGT cycle. The GCC of flue gas mixture touched at any of the vertex without intersection with GCC of steam forms optimal integration of STIGT cycle, which is represented by pinch point. The other parameters $h_{net}$, heat supplied, and cycle efficiency are determined as appropriately per unit mass of air.

![Figure 3. Targeting $S_i$ at maximum superheat temperature](image)

Figure 3. Targeting $S_i$ at maximum superheat temperature

Similar to this, if steam is heated up to saturated temperature, cycle integration condition is at minimum superheat temperature, however, steam ratio, $S_i$ is having maximum value. This integration is presented for maximum steam rate condition and determined using Equation 1 to 4 but for saturated steam condition. The proposed methodology is explained with the help of example in next section.

5. **Illustrative example:**
Consider advanced gas turbine cycle STIGT with design data given in Table 1. Note that all calculations are carried out per unit mass of air with steam rate varied to illustrate the proposed methodology. The minimum approach temperature for GCC of steam and flue gas mixture is 50 K.

**Table 1.** Gas turbine design data

| Parameter                        | Value  | Parameter                        | Value  |
|----------------------------------|--------|----------------------------------|--------|
| Gas turbine inlet temperature ($T_{gi}$), K | 1273   | Minimum approach temperature ($\Delta T$) K | 50     |
| Ambient temperature ($T_a$), K    | 303    | Combustion efficiency ($\eta_{cc}$) | 0.98   |
Gas turbine efficiency ($\eta_{gt}$) 0.9  
Specific heat capacity of gas at const pressure ($C_{pg}$), kW/kgK 1.148  
Sp. heat capacity of air at const pressure ($C_{pa}$), kW/kgK 1.005  
Ratio of specific heat capacities gas ($\gamma_g$) 1.315  
Ratio of specific heat capacities air ($\gamma_a$) 1.4  
Net calorific value of fuel (CV), MJ/kg 42.3  
Enthalpy of steam at $T_{ST}$ ($h_{ST}$), kJ/kg 2716  
Water inlet temperature ($T_{wi}$), K 298  
Stack temperature ($T_{ST}$), K 393

Using the Equation 1 to 4 for saturated steam condition, maximum steam ratio $S_{max}$ is determined for various pressure ratios. Similarly, using Equations 2 to 5, minimum steam ratio $S_{min}$ is determined for the same pressure ratios. The graph, pressure ratio (PR) Vs. steam ratio is plotted for minimum and maximum steam ratios as shown in Figure 4. Maximum superheat temperature of steam is possible up to temperature of gas mixture at gas turbine outlet with pinch temperature ($T_{go} - \Delta T$) as shown in Figure 3. At this condition, steam is supplied to combustion chamber at highest possible temperature, heated using gas turbine exhaust flue gas mixture, which results in $S_{min}$ with maximum efficiency. This maximum possible temperature is limited by temperature of the flue gases and further heating of mixture of steam and flue gases is carried out in combustion chamber. On the other side, for saturated condition, steam heated from gas turbine exhaust flue gas mixture is at saturated condition supplied to combustion chamber for $S_{max}$ for lower efficiency but higher net work. These conditions are represented in Figure 4. Region of $S_r$ lower than $S_{min}$ is showing high stack losses and region higher than $S_{max}$ is presenting steam quality at the entry to combustion chamber as wet.

Figure 4. Integration at $S_{max}$ and $S_{min}$

Figure 5. Efficiencies and net work at $S_{max}$ and $S_{min}$

Figure 5 is useful for selecting the appropriate steam condition so that selected system is optimal for given condition. For $S_{min}$, with PR between 8-9, efficiency is optimal and $W_{net}$ is maximum (at $S_r =$
0.205). However, for \( S_{\text{max}} \), \( W_{\text{net}} \) is maximum at lower pressure ratio (PR=3), but with lower efficiency. For entire range of PR, efficiency is higher for minimum \( S_{\text{m}} \), and \( W_{\text{net}} \) is higher for \( S_{\text{max}} \).

6. Conclusions:
The pinch analysis based methodology is proposed for investigation on steam injected gas turbine (STIGT) cycle. The proposed methodology is very useful for appropriate selection of steam ratio required for design of STIGT. The new plot of PR versus steam ratio \( (S_{\text{m}}) \) gives various regions of integration showing the appropriate space for feasible integration where design parameters can be selected based on objectives. Additionally, plot of overall efficiency and net work verses steam ratio is utilized for new system design as well as retrofitted system. For retrofitted system, at given pressure ratio, there are two objectives either maximum efficiency or maximum net work for design of STIGT system. In case of new design, initially, objective is fixed and based on it PR can be determined. Practically, the limiting value of steam ratio is 0.3. Considering this limitation, appropriate pressure ratio can be selected. For maximum overall performance, it is advisable to go for a STIGT plant with \( S_{\text{min}} \) at optimal PR in the range of 7 to 9 for an illustrative problem. On the other side, for maximum steam ratio with same condition, \( W_{\text{net}} \) is slightly higher compared to \( S_{\text{min}} \). Higher efficiency indicates less pollution due to flue gases leads to make environment clean and have more possibility to adhere the stringent environmental norms. Higher net work output indicates more energy available for use but with little lower efficiency.

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