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Parametric analysis of regenerative air bottoming combined cycle power plant

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ABSTRACT

Exhaust of simple, reheat and inter-cooling cycle of gas turbine cycle posses a lot of energy. Sometime this energy is so much that it can run another cycle or it can be used to heat the compressed air from the compressor to the combustion charmer that results to increase the overall efficiency of the plant. Air Bottoming Cycle (ABC) was proposed as an alternative for the conventional steam bottoming cycle. In spite of the cost of reducing hardware installations it could achieve a thermal efficiency of 80%. This paper is the parametric analysis of regenerative ABC Combine Cycle. The variables are compression ratio of topping cycle, peak temperature of the combustion chamber and mass flow rate of bottoming cycle. The result shows the gain in net work output as well as efficiency of combined cycle is 14% to 33%.

Introduction

In 1937 gas turbine was first introduced by Brown Boveri of Switzerland [1]. The early gas turbines had a thermal efficiency of only17%[1]. It has been shown that the thermal efficiency of a gas turbine can be increased by raising the pressure ratio and the turbine inlet temperature (TIT), and by using the turbine exhaust energy in a thermal recuperation process in a bottoming cycle [2,3]. Datta et al. [4] provided both energy and exergy analyses of an externally fired gas turbine (EFGT) cycle with an integrated biomass gasifier. They also study the effects of operating parameters like the compression ratio and turbine inlet temperature. They showed that the specific air flow, associated with the size of the plant equipment, decreased with the increase of the pressure ratio and found that an increase in the turbine inlet temperature reduced the specific air flow.

Wicks [5] derived the concept of Air Bottoming Cycle (ABC) from the theory of ideal fuel burning engines by comparing the engines with the Carnot cycle. The air bottoming cycle may be employed to utilize the heat rejected from the gas turbine. Korobitsyn [6] considered and used the cycle as a compact and simple bottoming cycle in various applications such as upgrading option for simple gas turbines in the off shore industries. The technical and economical feasibility of ABC has also been evaluated; where hot air from the air turbine is supplied to food processing industries. Combining the gas turbine cycle with an air bottoming cycle (ABC) is another method that has been introduced to increase the performance of a gas turbine [7]. In a review paper, Poullikkas [8] reported that the output power was increased by 18-30% in the ABC cycle compared to that of the simple gas turbine. The efficiency was also increased up to 10 percent. Korobitsyn in [6] highlights that the combination of a gas turbine with an ABC results of a high efficiency Combined Heat and Power (CHP) plant that provides clean, hot air for process needs.

Najjar et al. [9] in their parametric study on the efficiency of an ABC cycle found that for a compression ratio of 10 in the topping cycle and 2 in the bottoming cycle, and a TIT of 1400 K, the thermal efficiency can be increased to about 49%. A.K.Tiwari et.al. [10] in their study simultaneously vary the compression ratio of topping and bottoming cycle and beside this the other variables are TIT and mass flow rate & number of intercooler in bottoming cycle. They found that optimum point for this system is found to be, rp1= 6, rp2=12, mab=72 of air bottoming cycle with two intercoolers at turbine inlet temperature of 1400k.

Going through the literature, it is revealed that the use of Air Bottoming cycle in conjunction with the gas turbine topping cycle increases the overall efficiency of the cycle. However, the use of regenerative in the topping cycle with ABC has not been studied. So, in the present work, power optimization analysis of combine cycle plant has been attempted.

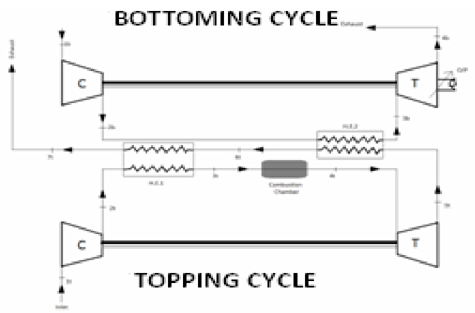

Figure 1

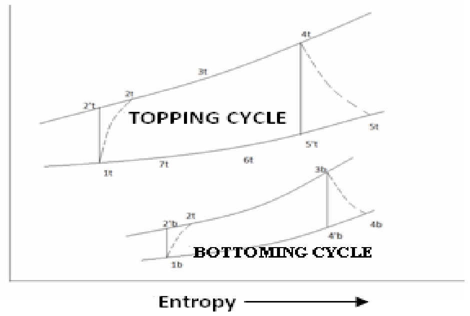

Figure 2

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Analysis of Topping Cycle

In topping cycle the air is compressed in compressor from 1 to 2 (refer figure 1) where its temperature raises from T1t to T2t.The compressed air then enter the combustion chamber where the combustion of fuel takes place. This result in rise of temperature of combustion product from T3t to T4t. The high temperature gases enter the turbine where it expands to the final temperature T5t.

Therefore expression for turbine work in topping cycle (Wt) is given by

$$w_{tt} = \overset{0}{m}_g \, c_{pg}\left(T_{4t} - T_{5t}\right) \qquad (1)$$

Where

$$T_{5t} = T_{4t}\left\{1 - \eta_t\left(1 - r_{pt}^{-\beta}\right)\right\} \qquad (1a)$$

And expression for compressor work in topping cycle (Wc) is given by

$$w_{ct} = \overset{0}{m}_a \, c_{pa}\left(T_{2t} - T_{1t}\right) \qquad (2)$$

Where

$$T_{2t} = T_{1t}\left\{1 + \frac{\left(r_{pt}^{\alpha} - 1\right)}{\eta_c}\right\} \qquad (2a)$$

Network of topping cycle

$$w_{nett} = w_{tt} - w_{ct} \qquad (3)$$

Heat supplied from the combustion chamber

$$q = \overset{0}{m}_g \, c_{pg} T_{4t} - \overset{0}{m}_a \, c_{pa} T_{3t} \qquad (4)$$

Effectiveness of first heat exchanger

$$\varepsilon_1 = \frac{T_{3t} - T_{2t}}{T_{2t} - T_{6t}} \qquad (5)$$

Therefore efficiency of the topping cycle

$$\eta_t = \frac{w_{nett}}{q} \qquad (6)$$

Analysis of Bottoming Cycle

Air at a temperature of T_{1b} enter the Compressor from where it at higher pressure and temperature T_{2b}.This high temperature air enter the heat exchanger number 2 where it absorb heat from the exhaust gas of topping cycle and in this way the temperature of air raises to T_{3b}. The high pressure and high temperature air after leaving the heat exchanger number 2 enters the turbine where it expands to the final temperature of T_{4b}.

Therefore expression for turbine work in bottom cycle (Wt) is given by

$$w_{tb} = \overset{0}{m}_{ab} \, c_{pa}\left(T_{3b} - T_{4b}\right) \qquad (7)$$

Where $T_{4b} = T_{3b}\left\{1 - \eta_t\left(1 - r_{pb}^{-\alpha}\right)\right\}$

And expression for compressor work in bottoming cycle (Wc) is given by

$$w_{cb} = \overset{0}{m}_{ab} \, c_{pa}\left(T_{2b} - T_{1b}\right) \qquad (8)$$

$$T_{2b} = T_{1t}\left\{1 + \frac{\left(r_{pb}^{\alpha} - 1\right)}{\eta_c}\right\}$$

Where

Effectiveness of second heat exchanger

$$\varepsilon_2 = \frac{T_{3b} - T_{2b}}{T_{5t} - T_{2b}} \qquad (9)$$

Network of bottom cycle

$$w_{netb} = w_{tb} - w_{cb} \qquad (10)$$

Analysis of Combined Cycle

The net work of combine cycle is the net work of topping cycle plus net work of bottoming cycle is

$$w_{net} = w_{nett} + w_{netb} \qquad (11)$$

The expression for net efficiency of the combine plant is

$$\eta = \frac{w_{net}}{q} \qquad (12)$$

$$x = \left(\frac{\overset{o}{m}_g .C_{pg}.\beta.\eta_t.\eta_c}{\overset{o}{m}_{ab} C_{pa}.\alpha.T_{1b}}\right) T_{3b}$$

Let $\qquad (13)$

$$r_{pb} = \left(x\right)^{1/(\alpha+\beta)} \qquad (14)$$

From equation (1a), (9), (13), & (14) we can write

$$T_{3b} = A + B(T_{3b})^{\alpha/(\alpha+\beta)} \qquad (15)$$

Where

$$A = \left(1 - \varepsilon_2\right)\left(1 - \frac{1}{\eta_c}\right) T_{1b} + \varepsilon_2 . T_{4t} . \left\{1 - \eta_t\left(1 - r_{pt}^{-\beta}\right)\right\} \qquad (16)$$

$$B = \frac{\left(1 - \varepsilon_2\right)}{\eta_c} T_{1b} . C^{\alpha/(\alpha+\beta)} \qquad (17)$$

$$C = \left(\frac{\overset{o}{m}_g .C_{pg}.\beta.\eta_t.\eta_c}{\overset{o}{m}_{ab} C_{pa}.\alpha.T_{1b}}\right) \qquad (18)$$

From equation (5)

$$T_{3t} = T_{2t} + \varepsilon_1 . \left(T_{6t} - T_{2t}\right) \qquad (19)$$

For second heat exchanger

$$\overset{o}{m}_g .C_{pg}.\left(T_{5t} - T_{6t}\right) = \varepsilon_2 . \overset{o}{m}_{ab} .C_{pa}.\left(T_{3b} - T_{2b}\right) \qquad (20)$$

Therefore

$$T_{6t} = T_{5t} - \varepsilon_2\left(\frac{\overset{o}{m}_{ab} .C_{pa}}{\overset{o}{m}_g .C_{pg}}\right)\left(T_{3b} - T_{2b}\right) \qquad (21)$$

Results and Discussion

The above equations of topping cycle clear that the network as well as efficiency is the function of turbine inlet temperature (TIT) and compression ratio and the network of combine cycle is the complex function of turbine inlet temperature (TIT) , compression ratio of topping cycle and mass flow rate of bottoming cycle. This study covers the conditions under which the output of topping cycle as well as combine cycle will be optimized.

Topping cycle

The network of topping cycle is the function of compression ratio and TIT. The figure 3 shows that at a particular TIT the network of topping cycle increases with increase of compression ratio and it is almost constant at higher values of compression ratio. Also at a particular compression ratio the network of topping cycle is directly proportional to TIT. Moreover the figure 4 shows that, as the compression increases the efficiency of topping cycle first increases and then constant at higher values of TIT or decreases at lower values of TIT. One of the major reason behind that is upto to the compression ratio 6 the temperature at point 2t is less than 6t i.e. heat is supplied from the exhaust gasses to air after compressor in the topping cycle and beyond this compression ratio the temperature of compressed air at point 2t is more than the 6t this mean that exhaust gasses is used cool the compressed air in that case heat supplied from the combustion chamber is increased that results in decrease in efficiency of topping cycle.

From figure 5 it is clear to say that the network as well as efficiency of topping cycle increases with increases of TIT. At the peak value of TIT the work output is maximum at the compression ratio of 12 & efficiency will maximum at the compression ratio of 10.

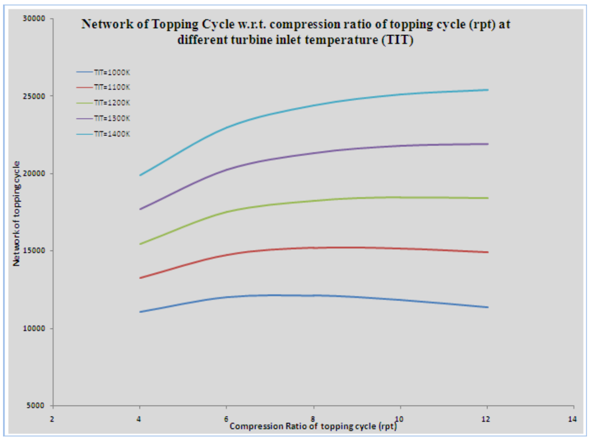

Figure 3

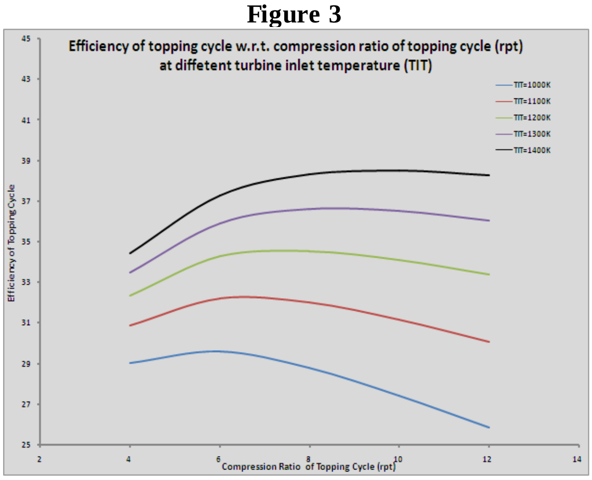

Figure 4

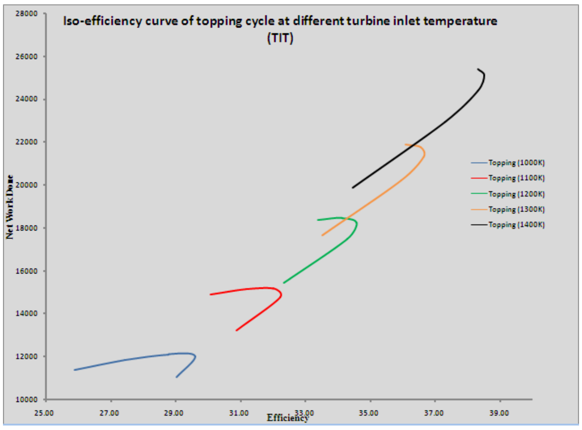

Figure 5

Figure 5 also shows that at the peak value of TIT, the increase in compression ratio results in increase in network as well as efficiency of the cycle. At TIT 1400K, the efficiency at the compression ratio of 8 &12 is same but the network is maximum at compression ratio of 12 where as the efficiency is maximum at the compression ratio of 10.

Combine cycle

The network & efficiency of combine cycle is the complex function of compression ratio, TIT and mass flow rate of bottoming cycle. The network of combine cycle is the sum of topping cycle and bottoming cycle this mean that the factor affecting the network of topping and bottoming cycle also affect the network of combine cycle. Figure 6 shows the variation of network and efficiency of combine cycle at a particular mass flow rate of bottoming cycle. The figure shows that both efficiency as well as network of combine cycle increases with increase of TIT.

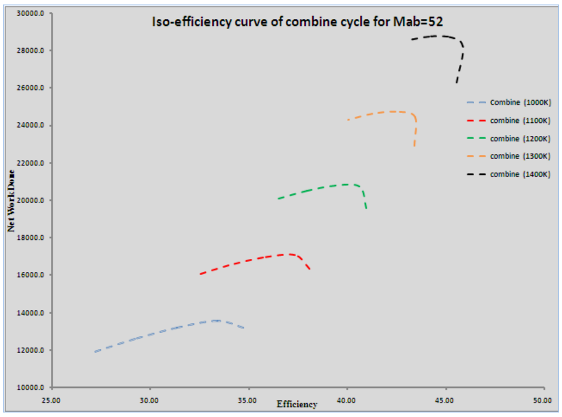

Figure 6

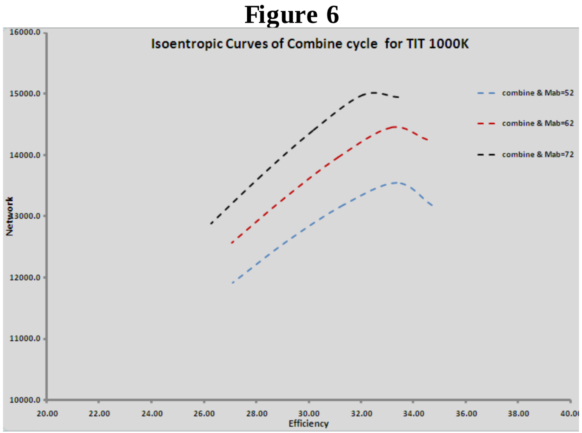

Figure 7

Figure 7 shows the variation of network and efficiency of combine cycle at a particular TIT for different mass flow rate of bottoming cycle. The figure shows that the network of combine cycle increases with increase of mass flow rate of bottoming cycle where as the efficiency of combine cycle decreases with increase of mass flow rate of bottoming cycle. Also with increase of compression ratio of topping cycle decreases in the lower portion of TIT. So the optimum conditions of network of combine cycle is that mass flow rate of bottoming cycle should be 72 kg/sec, TIT should be 1400K and compression ratio of topping cycle should be 10.

Conclusion

On the basis of above analysis on topping, bottoming as well as combined cycle outputs the following conclusion are made by varying the pressure ratio of topping cycle (rp1), turbine inlet temperature of topping cycle (TIT), mass flow rate in bottoming cycle (m_{ab}):

a) The network of topping cycle increases with increase of pressure ratio at higher values of TIT. At the pressure ratio of 12 and TIT 1400K one can get the optimum network of topping cycle.

b) The efficiency of topping cycle increases with increase of pressure ratio at higher values of TIT. The conditions under which efficiency of topping cycle will be maximum are pressure ratio of 10 and TIT 1400K for the cycle under study.

c) The network of combine cycle the sum of network of topping cycle and network of bottoming cycle. At the pressure ratio of topping cycle (r_{pt}) of 10 & mass flow rate of bottoming cycle (m_{ab}) is 72kg/s the network of combine cycle increases will be maximum with the condition the TIT should be 1400K.

d)The efficiency of combine cycle will be maximum under the condition of pressure ratio of topping cycle 6 and mass flow rate of bottoming cycle 52kg/s when the TIT is 1400K.

So the overall conclusion is that in order to achieve the optimum network of combine cycle the pressure ratio of topping cycle should be in the range of 8 to 12, TIT should be 1400K and m_{ab} should be 72 kg/s while for achieving the maximum efficiency of cycle the condition are pressure ratio of topping cycle should be in the range of 8 to 12, TIT should be 1400K and m_{ab} should be 52 kg/s.

NOMENCLATURE

T_{1t} : Compressor inlet temperature of topping cycle
T_{2t} : Compressor exit temperature of topping cycle
T_{3t} : Turbine inlet temperature in topping cycle
T_{4t} : Turbine exit temperature from topping cycle
T_{1b} : Compressor inlet temperature of bottoming cycle
T_{2b} : Compressor exit temperature of bottoming cycle
T_{3b} : Turbine inlet temperature in bottoming cycle
T_{4b} : Exhaust Temperature from air turbine
W : Work output
W_{nett} : Net work of topping cycle
W_{netb} : Net work of bottoming cycle
W_{net} :Net work of Combine Cycle
ϵ_1 : Effectiveness of First Heat Exchanger
ϵ_2 : Effectiveness of Second Heat Exchanger
r_{p1} : Pressure ratio of topping cycle
r_{p2} : Pressure ratio of bottoming cycle
η_c : Compressor efficiency
η_t : Turbine efficiency
$\eta_{topping}$ Efficiency of Topping Cycle
$\eta_{combine}$ Efficiency of Combined cycle
q Heat Supplied in combustion chamber
Cp Specific Heat

Variables

rpt : 4 to 12
T3t : 1000 to 1400K
Mab : 52 to 72 Kg/s

Constants

ηcomb = 0.96, ηt = 0.90, ηc = 0.90; T1t = T1b =298K
ma = 69Kg/s mf (Mass flow rate of fuel) = 1.32Kg/s
mg (Mass flow rate of gas in topping cycle) = ma+mf =70.32Kg/s
$\epsilon_1 = \epsilon_2 = 0.90$ Cpg (Specific Heat Of Gas) = 1.14KJ/KgK
Cpa (Specific Heat of air) = 1.005KJ/KgK
γ (For air) = 1.4 $\alpha = (\gamma-1)/\gamma = 0.285$
γ'(For Gas) = 1.33 $\beta = (\gamma'-1)/\gamma' = 0.248$

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