Energy and Exergy Analysis of Brayton-Brayton Hybrid Cycle for Power Plant Applications

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***Abstract*-- In this work energy and exergy analysis of a hybrid gas turbine cycle has been presented. The thermodynamic characteristic of Brayton- brayton cycle is considered in order to establish its importance to future power generation markets.**

The proposed cycle comprises of two brayton cycles, one acting as higher temperature topping cycle and the other by utilizing the thermal energy rejected this topping brayton cycle acts as the bottoming cycle. Mathematical modeling of Brayton- brayton cycle has been done at component level. Based on mathematical modeling, a computer code has been developed and the configuration has been subjected to thermodynamic analysis. Results show that, at any turbine inlet temperature (TIT), the plant specific work initially increases with increase of pressure ratio ($r_{p,c}$), and but at very high values of $r_{p,c}$, it starts decreasing. For a fixed value of $r_{p,c}$ with the increase in TIT, plant efficiency and specific work both increase. The cycle is best suited for applications where power requirement ranges between 300-550 kJ/kg. The exergy analysis shows that maximum exergy loss of around 27% occurs in during combustion in the plant.

***Index Terms*— Brayton-brayton cycle, exergy, exergy loss, gas turbine cycle, hybrid.**

I. INTRODUCTION

The increasing population of planet earth has been raising the demand for energy at a pace that continues to challenge the engineers around the world. While as the fossil fuels are depleting and one can imagine the future energy crisis unless some alternate cheap energy resources are developed. The increasing energy demand and depletion of fossil fuel resources inevitably necessitate for the optimum utilization of exhaustible fossil fuel and non-renewable energy resources. In this effort, a hybrid gas turbine based power cycle has been conceived for achieving maximum utilisation of thermal energy associated with the gas turbine exhaust.

In regard to the simple-cycle gas turbine technology, the major driver to enhance the engine performance has been the increase in cycle operating parameters (temperature and pressure) through advancements in materials and cooling methods. On-going development and near term introduction of advanced gas turbines has improved the efficiency of the simple-cycle operation more than 40%. Thermodynamic cycle developments, such as recuperation, mixed air steam turbines (MAST) are among the possible ways to improve the performance of gas turbine based power plants at feasible costs. Significant work in the field of advanced gas turbine based cycles has been done by Abdallah, H. and Harvey, S [1], Alabdoadaim, M et.al [2], Arrieta, F. R. P [3], Yadav R [4], Bianchi, M [5] , Chiesa. et al.[6] , Gabbrielli [7], Jonsson [8], Kuchonthara [9], Heppenstall [10], Horlock [11], Waldyr [12], Lukas [13], Poullikkas, A [14], Sanjay et.al.[15,16,17,18,19,20,21,22,23]. After reviewing recent technical papers by leading researchers Brayton-brayton cycle has been identified for detailed study.

II. NOMENCLATURE

c_p = specific heat…………..(kJ-kg^{-1}K^{-1})
gt = gas turbine
h = specific enthalpy………(kJ kg^{-1})
ΔH_r = lower heating value……(kJ.kg^{-1}K^{-1})
$\dot{m}$ = mass flow rate……….. (kg s^{-1})
Q = heat added/ removed during process
r_p = cycle pressure ratio
p = pressure………………..(bar)
T = temperature……………(K)
TIT = turbine inlet temperature (K) = combustor exit temperature
W = specific work………(kJ kg^{-1})
Gr = Gibbs free energy function =43890 kJ/kg

Greek symbols

ε = effectiveness ………..(%)
η = efficiency………………(%)
γ = ratio of specific heat at constant pressure and constant volume
υ = specific volume ………(m^{3}kg^{-1})

Subscripts

a = air , ambient
b = blade
bottoming = bottoming brayton cycle
c = compressor, coolant,
C = compression
comb = combustor
e = exit
f = fuel
g = gas

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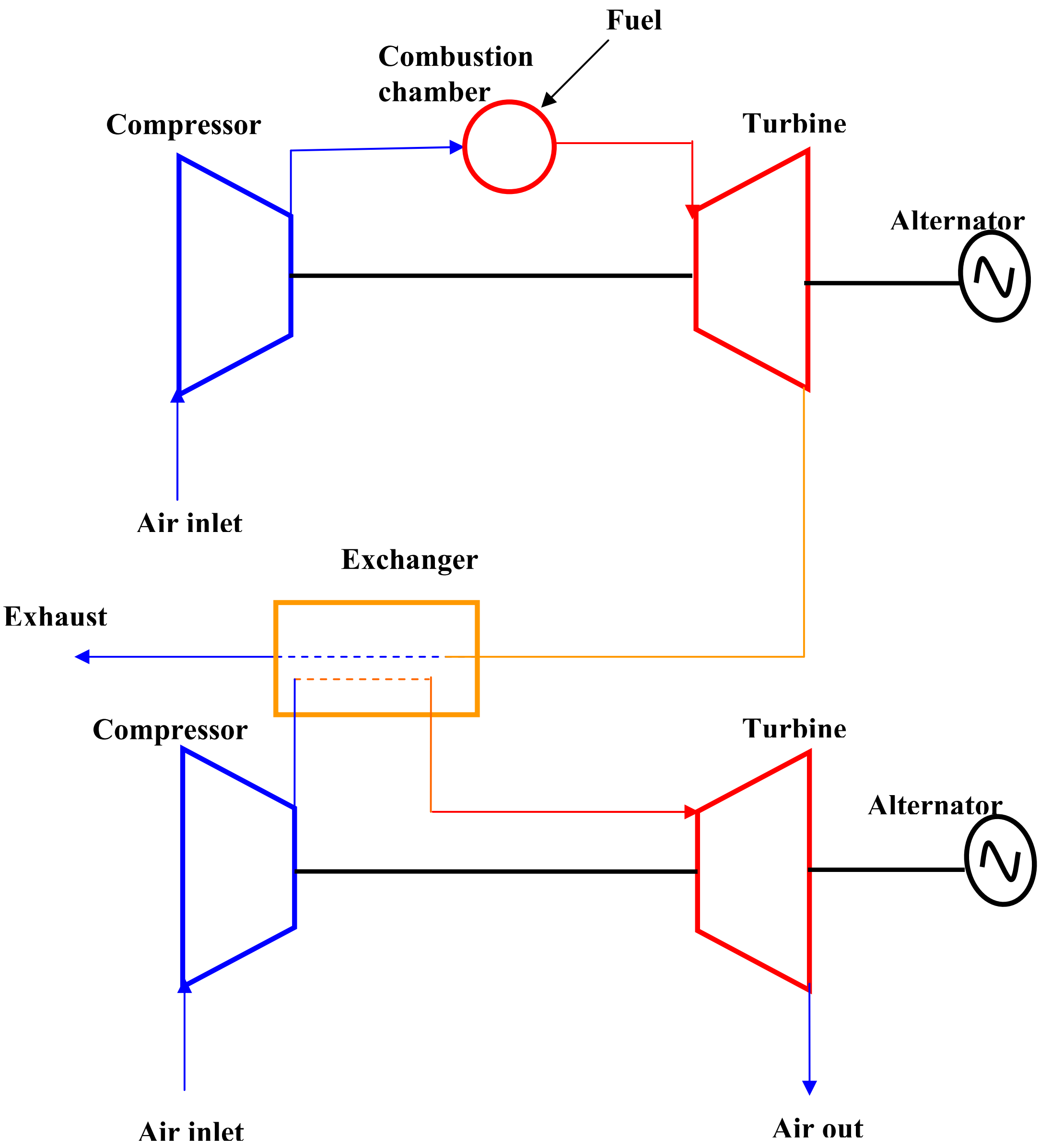

Fig. 1 Schematic of a Brayton-brayton hybrid cycle power plant

gt = gas turbine
he = heat exchanger
i = inlet, stage of compressor
in = inlet
j = coolant bleed points
net = difference between two values
p = pressure
plant = brayton-brayton cycle plant
topping= topping brayton cycle
z = cooled row stage

Acronym
C = Compressor
CC = Combustion chamber
GT = Gas turbine

III. BRAYTON-BRAYTON- CYCLE CONFIGURATION

The configuration identified for parametric study is built up of various types of components. Preheating of the inlet air of the bottoming brayton cycle can sufficiently improve its performance. The topping gas turbine exhaust can be applied in order to increase the temperature of the air, exiting the compressor of the bottoming brayton cycle. Hence the combustor, of the bottoming brayton cycle has been substituted by heat-exchanger heating the bottoming cycle compressor exit stream in the process saving on the fuel that would have to be burnt otherwise(Fig.1). Main components of this cycle are two gas turbine and gas-to-gas heat exchanger. Modeling of all these components/elements that constitute the cycle configuration has been done. Modeling of these components are based on mass and energy balance across the control volume boundary of each of these components. Modeling the various elements of a cycle and derived governing equations is detailed in the following section.

A. M*odeling of Components*

Modeling of various elements like working fluid/gas, compressor, combustor, and cooled gas turbines has been done in the earlier work [15,16,17]. Following are a few of the important equations of the model.

Enthalpy of air/gas, h = $\int_{T_o}^{T} c_p(T)\, dt$ (1)

Compressor work,

$W_{c,topping} = \dot{m}_{c,e}h_{c,e} + \sum m_{c,j}h_{c,j} - \dot{m}_{c,i}h_{c,i}$

(2)

Energy balance of combustor :

$\dot{m}_f \,.\Delta H_r \eta_{comb} = (\dot{m}_{g,e}h_{g,e} - \dot{m}_{a.in}h_{a.in})_{comb}$

(3)

The gas turbine work is the sum of the work done by all rows of bladings having open loop air-cooled blades.

$$W_{gt,topping} = \Sigma\dot{m}_{g.i}(h_{g.a_z} - h_{g.b_z})_{cooled} + \Sigma\dot{m}_{g.i}(h_{g.i} - h_{g.e})_{uncooled} \quad (4)$$

where ‘cooled’ and ‘uncooled’ in the equation represent rows of blade requiring cooling and rows of blade not requiring cooling.

B. Bottoming Gas Turbine Cycle

The bottoming cycle gas turbine is similar to a convential gas turbine except that the combustor of a conventional gas turbine has been replaced by a gas-to-gas heat exchanger which is being
fed by hot gases exiting the topping cycke gas turbine and which is used to heat up the compressed air exiting bottoming cycle compressor.

Compressor work, W_c = Compressor work,

$W_{c,bottoming} = \dot{m}_{c,e}h_{c,e} + \sum m_{c,j}h_{c,j} - \dot{m}_{c,i}h_{c,i}$

(5)

$$W_{gt,bottoming} = \Sigma\dot{m}_{g.i}(h_{g.a_z} - h_{g.b_z})_{cooled} + \Sigma\dot{m}_{g.i}(h_{g.i} - h_{g.e})_{uncoole} \quad (6)$$

Heat exchanger is used to transfer heat from the heated stream to the colder stream flowing through it. The energy balance equation of heat exchanger gives:

$$\dot{m}_h \cdot c_{p,h} \cdot \varepsilon_{he}\left[\left(T_{he,h}\right)_i - \left(T_{he,h}\right)_e\right] = \dot{m}_c \cdot c_{p,c} \cdot \left[\left(T_{he,c}\right)_i - \left(T_{he,c}\right)_e\right] \quad (7)$$

The exergy loss in the heat exchanger is given by

$$\Omega_{he} = m_{a,in}[E_{x,in} - E_{x,out}]_{air} + m_{g,in}[E_{x,in} - E_{x,out}]_{gas} \quad (8)$$

where ‘h’ stand for hot stream and ‘c’ stands for colder stream.

The gas turbine work is the sum of the work done by all rows of bladings having open loop air-cooled blades.

$$W_{gt} = \Sigma\dot{m}_{g.i}(h_{g.a_z} - h_{g.b_z})_{cooled} + \Sigma\dot{m}_{g.i}(h_{g.i} - h_{g.e})_{uncooled} \quad (9)$$

Table I. Input data for analysis for Brayton-Brayton Cycle

Component	**Parameters**
Gas property	C_p= f(T) Enthalpy h= ∫ C_p(T) dT
Ambient condition	T_a=288K P_a=1.013 bar Relative humidity=60%
Inlet section	Δp_{loss}=1 percent of entry pressure
Compressor(Topping and bottoming cycle)	Isentropic efficiency (η_c)=86% Mechanical efficiency(η_m)=98%
Combustor	Δp_{loss}=2% of entry pressure η_{cc}=98%
Fuel	Natural gas $(LCV)_f$=42000 kJ/kg Fuel inlet pressure = 110% of compressor exit pressure
Gas turbine(Topping and bottoming cycle)	Isentropic efficiency (η_t)=86% Mechanical efficiency(η_m)=98% Exhaust pressure=1.08 bar
Heat exchanger	Δp_{loss}=2% of entry pressure Effectiveness($\varepsilon_{rec)}$=92% Exhaust temperature for topping cycle=650K
Compressor(Bottoming cycle)	Pressure ratio=5
Alternator	Efficiency(η_{alt})=98.5%
For Exergy analysis	TIT=1700K & Pressure ratio=25

C. Cycle Performance Parameters

$$W_{gt,net} = \left(W_{gt,} - W_{c,}\right)_{topping} + \left(W_{gt,} - W_{c,}\right)_{bottoming} \quad (10)$$

$$W_{gt,overall} = W_{gt,net,topping} + W_{gt,net,bottoming} \quad (11)$$

Rational Efficiency, $\eta_{rat} = \dfrac{Wgt}{mf \cdot \Delta Gr}$

(12)

IV. RESULTS AND DISCUSSIONS

For predicting the performance of the Brayton-brayton-cycle, a computer code based on the modeling of various cycle components discussed in the previous section has been developed.

For predicting the performance of the Brayton-brayton-cycle, mathematical modeling of various cycle components has been discussed in previous section. Based on this modeling a computer code in C++ language has been developed. Results have been obtained for input data listed in Table I. and the results obtained have been plotted using graphic package ORIGIN 7.0. Based on results of exergy analysis, a Sankey diagram has been drawn for the cycle. The exergy distribution quantifies the losses in various elements of the cycle. The results (Design Monograms and Sankey diagrams) have been discussed.

Fig. 2. depicts performance map of a brayton-brayton cycle illustrating the variation of specific work and plant efficiency with pressure ratio ($r_{p,c}$) and turbine inlet temperature (TIT).

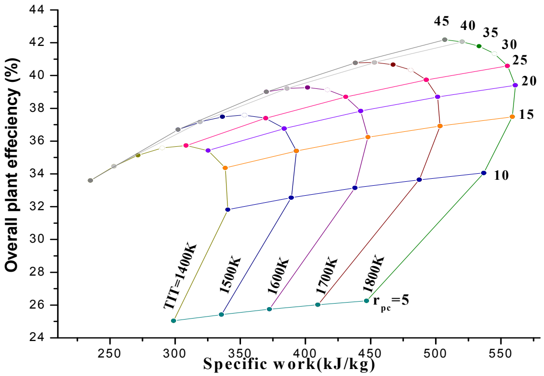

Fig. 2. Influence of TIT and cycle pressure ratio on thermal efficiency, specific work Brayton -Brayton gas turbine cycle

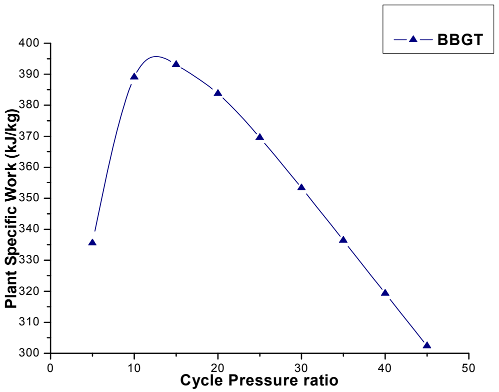

Fig. 3 Effect of cycle pressure ratio on plant specific work for Brayton-Brayton cycle at TIT=1500k

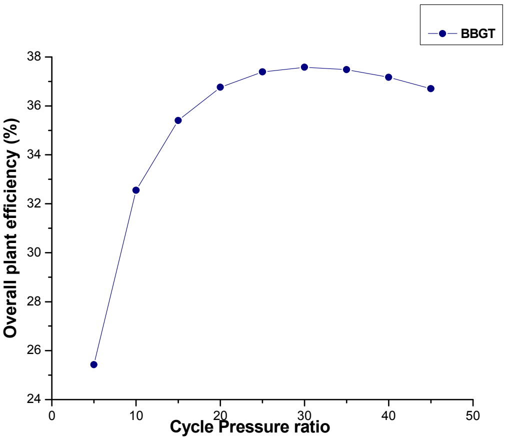

Fig. 4. Effect of cycle pressure ratio on plant efficiency for brayton-brayton cycle at TIT=1500K

It shows the variation of specific work and plant efficiency with compressor pressure ratio ($r_{p,c}$) and turbine inlet temperature (TIT).The input parameters have been shown in Table. 1. Fig. shows that at any TIT, up to $r_{p,c}$=20, specific work increases with increase in $r_{p,c}$, but beyond $r_{p,c}$ =20 it starts decreasing. At any TIT, plant efficiency increases with $r_{p,c}$ up to a certain value, beyond which it starts decreasing. At any $r_{p,c}$ overall plant efficiency and specific work increases with TIT over the plotted range.

Most of the gas turbines today operate at a TIT of 1500K, hence performance of the configuration at this value of TIT is shown in Fig. 3 and Fig. 4. Fig. 3 shows the effect of pressure ratio on plant specific work for the configuration. The graph shows the range of pressure ratio over which the cycle can operates and also the optimized value of specific work for the selected TIT which has been seen to be at $r_{p,c}$= 12. Fig. 4 shows the effect of pressure ratio on plant efficiency for the configuration. The graph shows the range of pressure ratio over which the cycle operates and also the optimized value of plant efficiency for the selected TIT at $r_{p,c}$=30.

Fig. 5. shows the exergy flow at $r_{p,c}$=25 and TIT=1700K among various components of the configuration. Gas turbine of topping cycle has the rational efficiency of about 37.26%, while that of bottoming cycle is only about 1.53% because TIT of bottoming cycle is limited by turbine exhaust temperature of topping cycle. Combustion chamber exhibits an exergy loss of about 28%. Overall exhaust gas exergy losses are about 15% and unaccounted exergy losses are about 8.25%.

V. CONCLUSIONS

The brayton-brayton cycle is a gas turbine hybrid cycle and its thermodynamic analysis has been carried out to ascertain its potential as a energy conversion system. From the analysis following conclusions can be drawn:

1) Brayton-brayton cycle provides the maximum available energy (about 40%)
2) Brayton-brayton cycle gives maximum work output between 450-550 kJ/kg.

Thus the cycle is found to be useful as a energy conversion cycle and performance in the above mentioned range.

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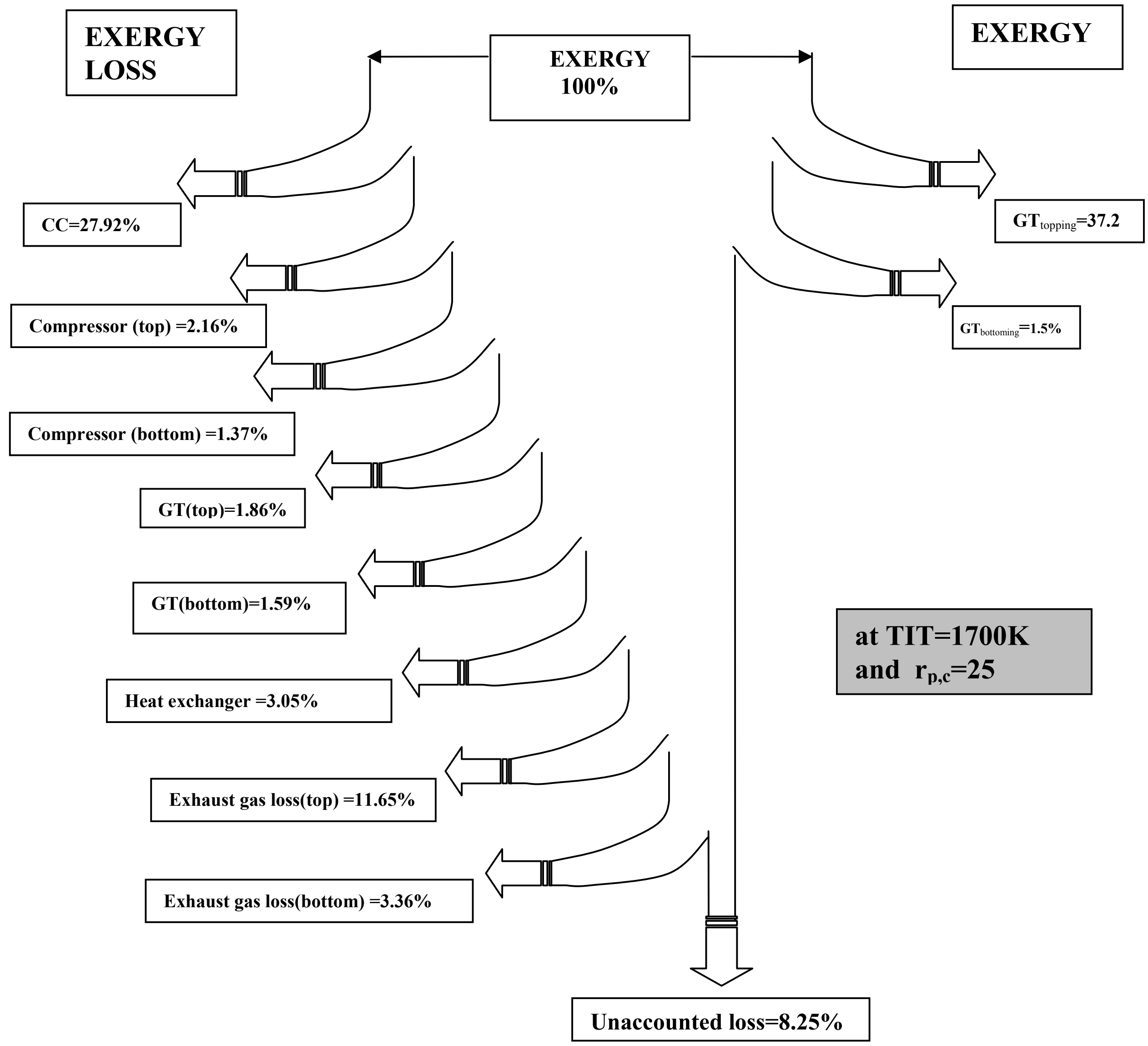

Fig. 5. Sankey diagram depicting exergy performance of a Brayton-brayton cycle

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