Performance Evaluation and Parametric Study of Basic and Reheated Cooled Gas Turbine Cycle: Exergy Analysis

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Abstract - *Present energy scenario depicts a continuous increase in gap between energy demand and energy supply with increasing electricity cost. Owing to increase in fuel prices electricity manufacturing companies have to adopt an energy conversion practice that must have higher performance side with lowest possible investment. Among the various techniques available, gas turbine with complex configuration for enhancing performance is the one. Cooled gas turbines allow manufacturers to go for higher turbine inlet temperature as allowable blade material temperature is 1150K only. Gas turbine blade cooling overcomes the metallurgical constraints that don't allow the turbine inlet temperature (TIT) to increase beyond a particular temperature, hence gas turbine blade cooling become a revolutionary area of research. In this regard present work deals with the thermodynamic analysis of basic gas turbine (BGT) and reheated gas turbine (RHGT) cycle incorporating air film blade cooling technique. The results of performance evaluation shows that exergy efficiency of the basic cooled gas turbine cycle is better as compared to the reheat cycle for the case TIT = 1800 K & r_{pc} = 30 while parametric study shows that coolant mass flow rate increases for both the configuration with increase in TIT while exergy efficiency curve of both the cycle shows falling nature with an increase in TIT at a fixed compressor pressure ratio.*

Key Words: Air film cooling, Blade cooling, Exergy analysis, Exergy efficiency, Parametric study, Plant Specific work Thermodynamic analysis, Reheated gas turbine

1. INTRODUCTION

Cooling of gas turbine blades has been a prime area of research since decades. According to report of International Energy Agency (Energy Outlook 2008) [1] the Global demand of energy has been forecasted to increase approximately 1.6 % per year for upcoming period of approximately 30 years. The regulation norms for cutting down the greenhouse gases emissions have forced the power producing units to adopt environment friendly (low emission) power producing techniques in the area of gas turbine and combined cycle. Various such techniques have been developed over the years, of which one is gas turbine blade cooling. Gas turbine blade cooling system now allows gas turbines operations at higher blade temperatures i.e. beyond the temperature constrained by metallurgical limits. The blade cooling includes blowing of compressed air from the internal passages of the blades over it. Authors have published numerous research articles in gas turbine blade cooling with thermodynamic as well as thermoeconomic analysis [2-11]. Mithilesh Kumar Sahu et al. [2-4] have thermodynamically analysed the cooled gas turbine cycles based on energy and exergy analysis. Anupam Kumari et al. [5] have reported the exergoenvironmental analysis of intercooled gas turbine cycles with emission characterization and also stated that the cooled gas turbines are more environment friendly compared to uncooled gas turbines and other thermal power plants.

Mithilesh Kumar Sahu and Sanjay [6-11] have thermoeconomically analysed the complex cooled gas turbines with film air cooling technique and also reported the effect of film cooling on various thermoeconomic and thermodynamic performance parameters. A comparative analysis was carried out by Louis et al. [12] on open and closed loop cooling methods by using the mathematical model. The mathematical model uses the air and steam as cooling medium. Louis et al. [12] reported that the difference of temperature between turbine inlet temperature and blade material temperature majorly affect the gas turbine performance parameters. Chuan and Louis et al. [13] extends the work and developed a mathematical model which determines the coolant mass flow rate requirement for particular gas turbine output. They also performed the comparative study on various inlet air cooling systems on and reported the effect of same on combined cycle performance. El-Masri [14] developed an Interactive computer code, named GASCAN by mathematical modelling of various gas turbine components describing cooled GT performance. Brieshet et al. [15] have suggested the possibility of thermal efficiency to be 60%. The author suggested the closed loop steam cooling as the best alternative. A detailed comparative study of advanced combined cycle alternatives with bottoming cycle has been carried out by Bolland [16]. Young and Wilcock [17] described the basic thermodynamics of an air film cooled gas turbine model. The author suggested that these cycles include varying composition of gas mixtures and hence a realistic modelling of the components must be done. He further advocates the importance of cooling losses while estimating the performance of a cooled cycle. Sanjay et al. [18] reported the component wise thermodynamic modelling of advanced combined cycle for the assessment of enhanced performance. The result illustrates that increase in the TIT has a positive effect over the overall plant efficiency i.e. efficiency is increased with respect to the reference cycle. Sanjay [19] investigated a parametric study to outline the energetic and exergetic performance of combined cycle. The article highlights that with increasing TIT and r_{pc} values, the exergy destruction values decreases. Sanjay et al. [20] carried out a detailed energy and exergy analysis for reheat gas steam combined cycle and observed the superiority of closed-loop-steam-cooling over air-film cooling. The author further reveals that the reheat gas-steam combined cycle shows an enhance thermal efficiency and plant specific output with closed-loop-steam-cooling in comparison to basic gas-steam combined cycle with air film cooling. Alok and Sanjay [21] carried out a detailed study investigating thermodynamic assessment of the performance of gas turbine and combined cycle incorporating inlet cooling techniques. The article focuses the comparative study of impact of two different inlet air cooling methods namely vapour compression and vapour absorption. The author advocates the use of vapour compression cooling method in combined cycle for higher plant performance. A detailed report over thermodynamic performance of combined cycle power plant has been submitted incorporating seven different methods of blade cooling in a technical paper by Sanjay et al. [22]. A cogeneration cycle based on gas turbine has been taken for study by Sanjay et al. [23]. The author investigated the effect of different gas turbine blade cooling on the discussed cycle. The maximum power to heat ratio has been observed for steam cooled internal convection while minimum has been observed for internal convection cooling taking air as the coolant. A. K. Mohapatra and Sanjay [24] studied the parametric study of variation in performance parameter such as TIT, compressor pressure ratio on a cooled gas turbine plant with two inlet air cooling techniques. The authors suggest that integration of two techniques have a positive effect over the plant performance. Anupam Kumari and Sanjay [25] studied the effect of parameters affecting the exergetic and emission characteristics of gas turbine cycles. The author advocates that intercooled configuration should be preferred over basic one as it delivers higher specific power output and plant efficiency. The emission performance of IcGT is better than basic cooled gas turbine cycle.

The present paper deals with the exergetic performance evaluation of reheated cooled gas turbine cycle with basic cooled gas turbine cycle incorporating air film cooling technique. Film cooling is the widely accepted cooling technology where the surface of the blade gets covered with a thin film of air which acts as a thermal barrier and separates the blade surface to make a direct contact with hot gases coming out of combustion chamber [26].

2. SYSTEM CONFIGURATIONS

The schematic diagram of basic and reheated gas turbine based power plant is shown in Figure 1 and Figure 2 and depicts the conventional way of gas turbine operation with blade cooling. The novelty of this work is consideration of blade cooling in the performance evaluation of aforesaid cycles. As real gas turbine engines works on blade cooling principles hence this work provides significant scientific merit to the research field.

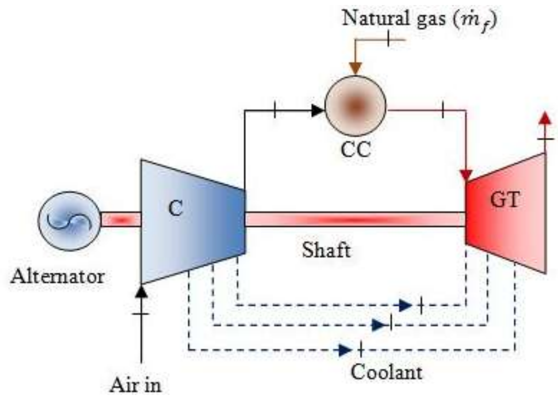

Figure 1: Schematic diagram of basic gas turbine cycle with air film blade cooling

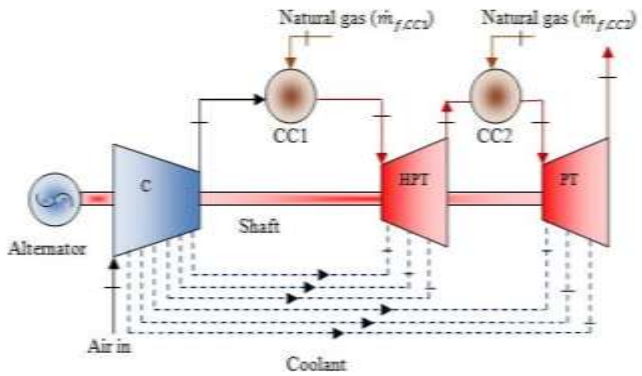

Figure 2: Schematic diagram of reheated gas turbine cycle with air film blade cooling

3. MODELLING AND GOVERNING EQUATIONS

3.1 Air/gas Model [27]

$$c_{pa} = 1.023204 - 1.76021 * 10^{-4}T + 4.0205 * 10^{-7}T^2 - 4.87272 * 10^{-11}T^3 \quad (1)$$

$$c_{pg} = [15.276826 + 0.01005T - 3.19216 * 10^{-6}T^2 + 3.48619 * 10^{-10}T^3 + x_0(0.104826 + 5.54150 * 10^{-5}T - 1.67585 * 10^{-8}T^2 + 1.18266 * 10^{-12}T^3)]/V \quad (2)$$

$$h = \int_{T_0}^{T} c_p(T)\, dT \quad (3)$$

$$\varphi = \int_{T_0}^{T} c_p(T) \frac{dT}{T} \quad (4)$$

$$s = \varphi - R\ln(\frac{p}{p_0}) \quad (5)$$

$$E = h - T_0.s \quad (6)$$

3.2 Compressor Model [7]

$$p_e = p_i * r_{pc} \quad (7)$$

$$T_e = T_i\{1 + \frac{1}{\eta_{AC}}[(\frac{p_e}{p_i})^{\frac{\gamma_a - 1}{\gamma_a}} - 1]\} \quad (8)$$

$$\dot{W}_C = \dot{m}_e \cdot h_e + \sum \dot{m}_{cool,j} \cdot h_{cool,j} - \dot{m}_i \cdot h_i \quad (9)$$

3.3 Combustion Chamber Model [7]

$$\dot{m}_e = \dot{m}_i + \dot{m}_f \quad (10)$$

$$\dot{m}_f \cdot LHV \cdot \eta_{cc} = \dot{m}_e \cdot h_e - \dot{m}_i \cdot h_i \quad (11)$$

$$\dot{m}_f = \frac{[\dot{m}_i \cdot h_e - \dot{m}_i \cdot h_i]}{[\eta_{cc} \cdot LHV - h_e]} \quad (12)$$

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \quad (13)$$

$$p_e = p_i(1 - \Delta p_{cc}) \quad (14)$$

3.4 Cooled Gas Turbine Model [7]

Air Film cooling:-Figure 3 depicts the main stream hot gases and coolant air passage. From figure it can be seen that how coolant air is emerging out from the cooling holes and creates a film which restricts the direct contact of hot main stream gases with the blade surface. This leads to increase in life span of the blade as well as air film cooling has its own advantage of mixing with mainstream gases and giving the edge of higher mass flow rates for expansion compared to closed loop cooling technics.

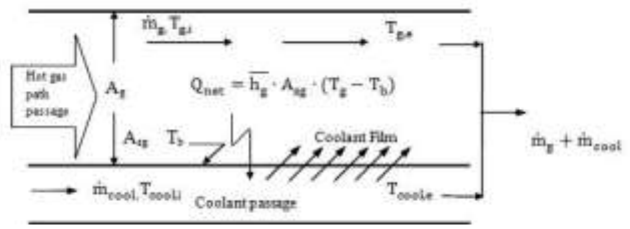

Figure 3: Model of air film cooling of turbine blade

$$\zeta = \frac{\dot{m}_{cool}}{\dot{m}_g} = \left(1 - \eta_{iso,air}\right)\frac{St_i \cdot S_g}{\varepsilon_{cool} \cdot t.\cos\alpha} * \frac{c_{pg}(T_{g,i} - T_b)}{c_{p,cool}(T_b - T_{cool,i})} * F_{sa} \quad (15)$$

$$p_3 = p_2(1 - \Delta p_{cc}) \quad (16)$$

The temperature and pressure of gas turbine exhaust stream and power output is given by the relation:

$$T_e = T_i\{1 - \eta_{GT}[1 - (\frac{p_i}{p_e})^{\frac{1-\gamma_g}{\gamma_g}}]\} \quad (17)$$

$$\dot{W}_{GT} = \left(\dot{m}_i h_i + \sum \dot{m}_{cool,j} h_{cool,j} - \dot{m}_e h_e\right) * \eta_{mech} \quad (18)$$

$$\dot{W}_{net} = \dot{W}_{GT} - \dot{W}_C \quad (19)$$

4. RESULT AND DISCUSSION

A MATLAB code [28] has been developed to simulate the performance of proposed gas turbine cycle configurations. To simulate the gas turbine performance some key design and operating parameters need to be specified and the same has been detailed in Table 1. The simulation results have been discussed with the help of various illustrating graphs.

Table 1: Key parameters for analysis of proposed cycle [7, 9, 18 and 20]

Components	Design/Operating parameters	Adopted value	Unit
Gas Properties	$c_p = f(T)$		kJ/kgK
	$h = \int_{T_0}^{T} c_p(T)\, dT$		kJ/kg
Compressor	η_{AC}	88	%
	η_{mech}	98.5	%
	r_{pc}	20-30	-
Combustion Chamber	η_{CC}	99.5	%
	p_{loss}	2.0% of p_{entry}	bar
	LHV	42.0	MJ/kg
	$p_{fuel\ line}$	1.5*p_{cc}	bar
Turbine	η_{GT}	90	%
	$p_{exhaust}$	1.08	bar
	T_b	1150	K
	TIT	1500-1800	K

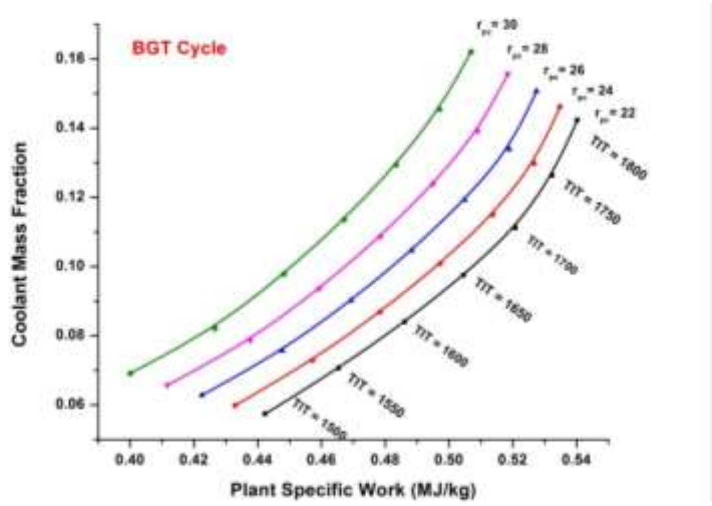

Figure 4: Effect of TIT and r_{pc} on coolant mass fraction and plant specific work for BGT cycle

Figure 4 depicts the variation of plant specific work output of basic gas turbine cycle with coolant mass fraction at different TIT and r_{pc}. It can be clearly seen that coolant mass flow rate increases, as the compressor pressure ratio increases at a fixed TIT value while plant specific work output decreases at the same parameters. The increase in coolant requirement is driven by the fact that as we move on for higher r_{pc} it also results increase in temperature of coolant air available at compressor bleed points and of course higher r_{pc} needs more compressor work which ultimately results decrease in plant specific work. Coolant mass fraction and plant specific work both shows an increasing trend for fixed r_{pc} value with increasing TIT values. The rising tendencies of curve for both parameters are in line with the concept of heat transfer (for higher temperature more amount of coolant required) and thermodynamics (energy at higher temperature has more potential).

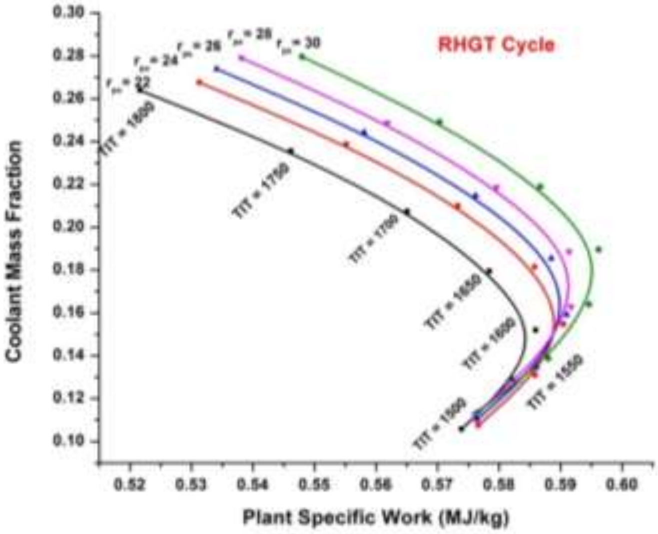

Figure 5: Effect of TIT and r_{pc} on coolant mass fraction and plant specific work for RHGT cycle

Figure 5 represents a variation of coolant mass fraction with plant specific output of reheated cooled gas turbine with varying TIT and r_{pc} values. The graph predicts the similar trend with the previous literatures as the values of TIT is increased from 1500K to 1800K keeping r_{pc} value constant, the coolant mass fraction value increases because higher TIT causes more amount of coolant to be bled from compressor for the cooling of stages while the plant specific work output initially increases sharply and again starts decreasing after a certain TIT value. The diagram further describes that as r_{pc} values are increased along a fixed TIT value the coolant mass fraction ratio shows slight increment in the coolant mass fraction up to an r_{pc} while again it shows decline behaviour. It occurs because of increase in r_{pc} value causes more number of turbine stages to be cooled. The diagram describes that on increasing the r_{pc} value along a fixed TIT values the plant specific work output increases for RHGT cycle.

In Figure 6 behaviour of coolant mass fraction with second law plant efficiency for the basic cooled gas turbine cycle is depicted. It is observed from Figure 6 that as TIT values increase from 1500K to 1800K at the same r_{pc}, the curve of coolant mass fraction shows an increase trend while the exergy efficiency of the cycle decreases at the same parameters. The graph further describes the behaviour of increasing r_{pc} values over fixed TIT values which further shows an increase in both coolant mass fraction as well as exergy efficiency due to the reasons explained earlier

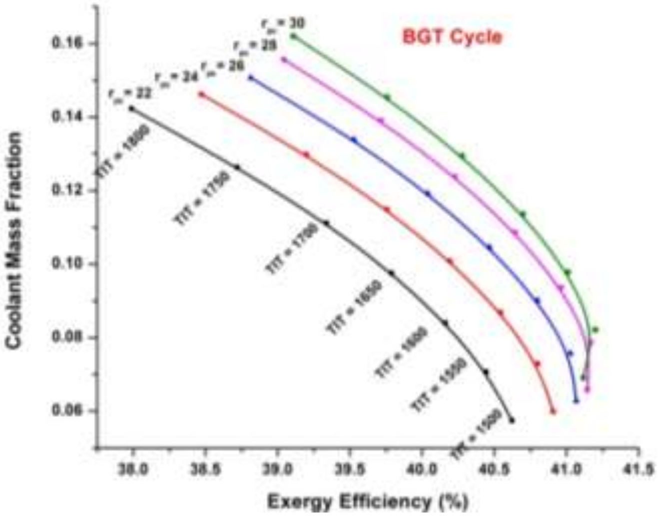

Figure 6: Effect of TIT and r_{pc} on coolant mass fraction and exergy efficiency for BGT cycle

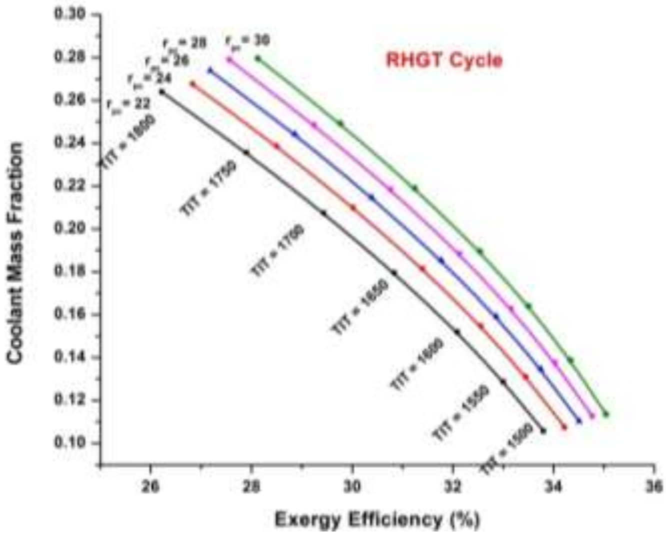

Figure 7: Effect of operating parameters on coolant mass fraction and exergy efficiency for RHGT cycle

Figure 7 describes the performance behaviour of coolant mass fraction of reheated cooled gas turbine cycle with second law efficiency (exergy efficiency). Figure depicts that coolant mass fraction and exergy efficiency both shows increasing trend with increase in r_{pc} while keeping a fixed value of TIT. It is due to the fact that higher r_{pc} results increase in coolant air temperature as well as it also results saving in mass flow rate of fuel required for combustion. An increase in TIT value at a fixed r_{pc} shows an increase in coolant mass fraction (higher temperature as well as more number of stages required cooling) while the value of exergy efficiency decreases on increasing the TIT (increase in fuel mass flow rate).

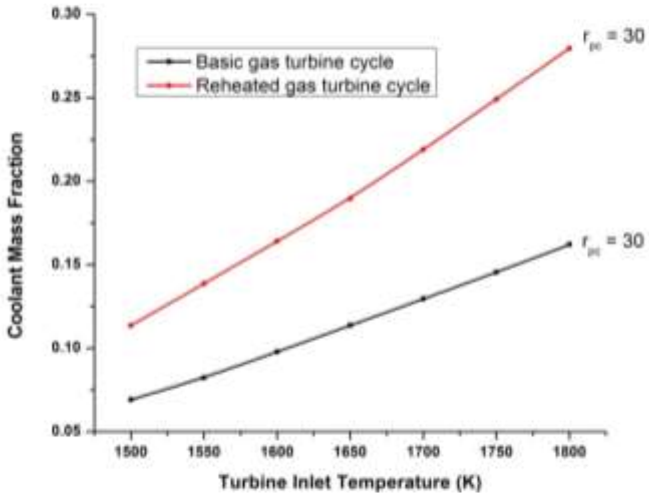

Figure 8: Comparative analysis of BGT and RHGT for coolant mass fraction with TIT variation (fixed r_{pc})

In Figure 8, the variation of coolant mass fraction with the TIT values for both basic and reheat cooled gas turbine cycle at a fixed value of r_{pc}=30 has been illustrated. The values of coolant mass fraction is increased along with the increase in TIT in both basic and reheat cooled gas turbine cycle because higher TIT causes higher coolant mass fraction for more number of stages to get cooled. The coolant requirement for the both basic and reheat gas turbine cycle increases with rise in TIT but the trend followed in basic cooled gas turbine is little gradual while for cooled reheated gas turbine it follows a little sharp trend.

Figures 9 explain the behaviour of exergetic performance and specific work of basic and reheat configurations of gas turbine cycle. The column chart clearly indicates that exergy efficiency of basic gas turbine is better as compared to reheat cycle for same operating conditions. The combustion chamber (CC) is the main source of exergy destruction and as in reheat cycle fuel required is also higher that is the reason for lesser exergy efficiency in case of reheat cycle. The column chart also compares the plant specific work output of both the cycles which is greater in case of RHGT cycle. In reheat cycle expansion takes in two stages of turbine, which results higher specific work output compare to BGT cycle for same operating parameters.

5. CONCLUSIONS

A systematic component modelling followed by exergy analysis of proposed basic and reheat gas turbine configurations has been performed. The analysis of simulated results presented in the previous section with the help graphs and charts suggests the following conclusions:

- The coolant mass fraction for both the BGT and RHGT increases with increase in TIT for fixed compressor pressure ratio.
- The specific work output of the BGT increases on increasing the TIT at a fixed r_{pc} while for the RHGT specific plant work initially increases sharply on increase in TIT and again it starts decreasing after a certain TIT.
- The exergy efficiency curve of both the cycle shows falling nature with an increase in TIT at a fixed compressor pressure ratio.
- Exergy efficiency of the basic cooled gas turbine cycle is better as compared to the reheat cycle for the case TIT = 1800K & r_{pc} = 30.
- Plant specific output is found to be more in case of reheat cycle as compared to basic cooled gas turbine for TIT = 1800K & r_{pc} = 30, as in reheat cycle the expansion takes place in two steps.

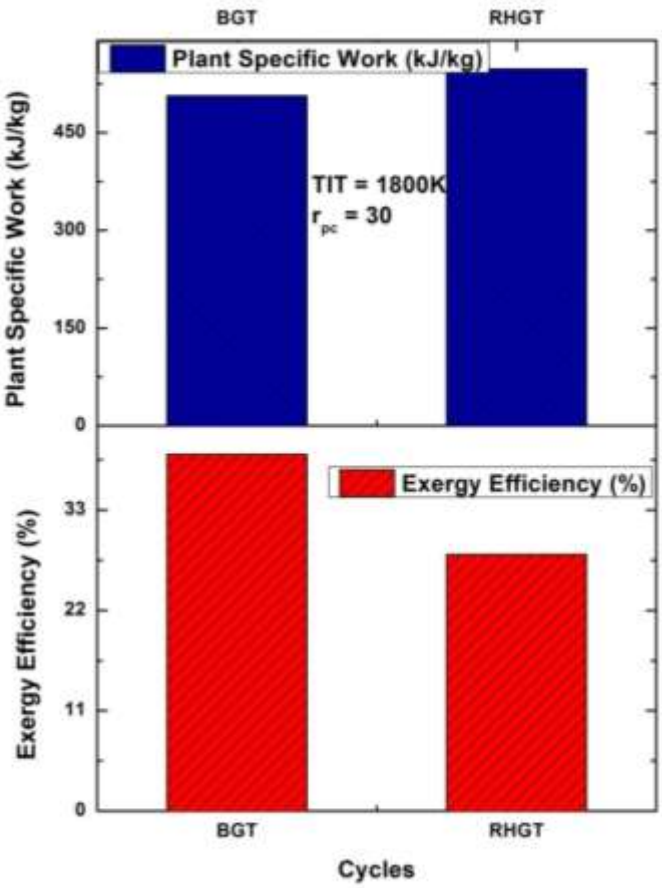

Figure 9: Comparative analysis of BGT and RHGT cycle for same operating conditions

REFERENCES

[1] Energy Outlook 2008. http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/weo2008.pdf

[2] Mithilesh Kumar Sahu, Sanjay, "Parametric Thermodynamic Analysis of Intercooled and Intercooled-Recuperated Gas Turbine Based Cycles",

Journal of Renewable Energy Science Technology & Economics, Vol. 1(1), pp.1-14, 2015.

[3] Mithilesh Kumar Sahu, Sanjay, Sudeep Lekurwale, Nitin Kumar M., Anupam Kumari, "Energy and Exergy Analysis of Complex Intercooled-Recuperated Gas Turbine Based Power Plant With Cooled Turbine Blades", ISST Journal of Mechanical Engineering, Vol. 5(1), pp.49-57, 2014.

[4] Mithilesh Kumar Sahu, Shivam Mishra, "Comparative Thermodynamic Performance Evaluation of Cooled Gas Turbine Plant", International Journal of Advanced Technology in Engineering and Science, Vol. 4(9), pp.1320-1330, 2016.

[5] Anupam Kumari, Tushar Choudhary, Y Sanjay, Pilaka Murty, Mithilesh Kumar Sahu, "Thermodynamic and Emission Analysis of Basic and Intercooled Gas Turbine Cycles". SAE Technical Paper 2015-01-2426, 2015, doi.org/10.4271/2015-01-2426

[6] Mithilesh Kumar Sahu, Sanjay, "Thermoeconomic Investigation of Different Gas Turbine Cycle Configuration's For Marine Application", SAE Technical, 2016-01-2228, 10/17/2016, doi.org/10.4271/2016-01-2228

[7] Mithilesh Kumar Sahu, Sanjay, "Investigation of the Effect of Air Film Blade Cooling on Thermoeconomics of Gas Turbine Based Power Plant Cycle", Energy, Vol. 115, pp.1320-1330, 2016. doi.org/10.1016/j.energy.2016.09.069

[8] Mithilesh Kumar Sahu, Sanjay, "Comparative Exergoeconomic Analysis of Basic and Reheat Gas Turbine with Air Film Blade Cooling", Energy, Vol. 132, pp.160-170, 2017. doi.org/10.1016/j.energy.2017.05.025

[9] Mithilesh Kumar Sahu, Sanjay, "Exergoeconomic Investigation of Power Utility Based on Air Film Blade Cooled Gas Turbine Cycle", Applied Thermal Engineering, Vol. 122, pp.738-746, 2017. doi.org/10.1016/j.applthermaleng.2017.05.052

[10] Mithilesh Kumar Sahu, Sanjay, "Thermoeconomic Investigation of Power Utilities: Intercooled Recuperated Gas Turbine Cycle Featuring Cooled Turbine Blades", Energy, Vol. 132, pp.160-170, 2017. doi.org/10.1016/j.energy.2017.07.083

[11] Mithilesh Kumar Sahu, Sanjay, "Comparative Exergoeconomics of Power Utilities: Air-cooled Gas Turbine Cycle and Combined Cycle Configurations". Energy, Vol. 139, pp.42-51, 2017. doi.org/10.1016/j.energy.2017.07.131

[12] Louis J.F. HiraokaK, El-Masri M. A., "A Comparative Study of Influence of Different Means of Turbine Cooling on Gas Turbine Performance", ASME, Paper no 83-GT-180, 1983.

[13] Chaun W.S., Louis J.F., "A Comparative Study of The Influence of Different Means of Cooling on The Performance of Combined Gas And Steam Turbine Cycle", Trans. of ASME J. Eng. Gas. Turbines Power, Vol. 106, pp.750-55, 1984.

[14] El-Masri M. A., "GASCAN- An Interactive Code for Thermal Analysis of Gas Turbine Systems, Trans. ASME J. Eng. Gas Turbines Power", Vol. 110, pp.201-09, 1988.

[15] Briesh M. S., Bannister R. L. Diakunchak I. S., Huber D. J., "A Combined Cycle Designed To Achieve Greater Than 60 Percent Efficiency", ASME J. Eng. Gas Turbine Power, Vol. 117, pp.734-741, 1995.

[16] O. Bolland, "A Comparative Evaluation of Advanced Combined Cycle Alternatives", ASME J. Eng. Gas Turbine Power, Vol. 113, pp.190-97, 1991.

[17] YOUNG J. B. and Wilcock R. C., "Modelling the Air-Cooled Gas Turbine: Part 1-General Thermodynamics", ASME Journal of Turbomachinery, Vol. 124, pp.207-13, 2002.

[18] Sanjay, Singh O., Prasad B. N., "Thermodynamic Modelling and Simulation of Advanced Combined Cycle for Performance Enhancement", Power and Energy Proc. IMechE, Vol. 222 Part A.

[19] Sanjay, "Investigation of Effect of Variation of Cycle Parameters on Thermodynamic Performance of Gas-Steam Combined Cycle", Energy, Vol. 36, pp.157-67, 2011.

[20] Sanjay, Singh O., Prasad. B. N., "Energy and Exergy Analysis of Steam Cooled Reheat Gas–Steam Combined Cycle", Applied Thermal Engineering, Vol. 27, pp.2779–90, 2007.

[21] Mohapatra A. and Sanjay, "Thermodynamic Assessment of Impact of Inlet Air Cooling Techniques on Gas Turbine and Combined Cycle Performance", Energy, Vol. 68, pp.191-203, 2014.

[22] Sanjay, Singh Onkar, Prasad B.N., "Influence of Different Means of Turbine Blade Cooling on The Thermodynamic Performance of Combined Cycle", Applied Thermal Engineering, Vol. 28, pp.2315–26, 2008.

[23] Sanjay, Singh Onkar, Prasad B. N., "Comparative Performance Analysis of Cogeneration Gas Turbine Cycle for Different Blade Cooling Means", International Journal of Thermal Sciences, Vol. 48, pp.1432–40, 2009.

[24] Mohapatra A. K., Sanjay, "Comparative Analysis of Inlet Air Cooling Techniques Integrated To Cooled Gas Turbine Plant", Journal of the Energy Institute, Vol. 88, pp.344-358, 2014.

[25] Kumari Anupam, Sanjay, "Investigation of Parameters Affecting Exergy and Emission Performance of Basic and Intercooled Gas Turbine Cycles", Energy, Vol. 90, pp.525-36, 2015.

[26] Laxminarayana Budugar, "Fluid Dynamics and Heat Transfer of Turbomachinery", John Wiley and Sons, 1996.

[27] YS Touloukian, Makita Tadash, "Thermo-physical properties of matter". The TPRC Data Series. Vol.6 IFI/PLENUNM: New York, Washington; 1970.

[28] MATLAB and Statistics Toolbox Release 2012b. The Math Works, Inc., Natick, Massachusetts, United States.