COMPARATIVE THERMODYNAMIC PERFORMANCE EVALUATION OF COOLED GAS TURBINE PLANT

Shivam Mishra[1], Mithilesh Kumar Sahu[2]

[1]Ph.D. Scholar, Mechanical Engg. Department, NIT, Jamshedpur, INDIA
[2]Ph.D. Scholar, Mechanical Engg. Department, NIT, Jamshedpur, INDIA

ABSTRACT

In recent era development of new high temperature materials and improved blade cooling technologies have made an encouraging impact on the gas turbine performance. The previous literature shows that gas turbine cycle performance is improved with increase in turbine inlet temperature (TIT). To achieve higher turbine inlet temperature we need to introduce some efficient blade cooling means. The present paper deals with the comparative analysis of gas turbine performance based on two different blade cooling schemes i.e. film cooling and convective cooling. The performance results have been expressed in terms of thermal efficiency, specific power output of the cycle which is a strong function of gas turbine blade cooling scheme. The independent variables considered in the present study are TIT, compressor pressure ratio and coolant inlet temperature. The parametric analysis of the present cycle includes the modeling of all components of gas turbine cycle and gas properties model have also been adopted.

Keywords: *Gas turbine cycle, energy analysis, blade cooling, Turbine inlet temperature, compressor pressure ratio.*

I. INTRODUCTION

Gas turbine blade cooling has been a main area of research since decades. The regulation norms for cutting down the greenhouse gases emissions have forced the power producing units to adopt cost effective power producing techniques in the area of gas turbine and combined cycle. Gas turbine blade cooling technique is one of the power enhancement techniques. . The gas turbine blade cooling increases the performance of cycle. In a blade cooling technique blowing of compressed air from the internal passages of the blades takes place over it. Many research articles have been published over blade cooling of gas turbine. A comparison of open and closed loop cooling methods has been carried out by Louis et al. [1] based on a mathematical model. Gas turbine cycle performance is majorly affected by the temperature difference between turbine inlet temperature and blade temperature. Chaun and Louis et al. [2] developed a mathematical model for the determination of coolant mass flow rate. They further conducted a comparative study over the effect of various inlet air cooling systems on the performance of combined cycle. El-Masri [3] developed an Interactive computer code named GASCAN based on the mathematical modeling of various components of gas turbine describing the performance of cooled gas turbine. Sanjay et al. [4] prepared a through report over thermodynamic performance of combined cycle power plant incorporating seven different methods of blade cooling. The study discusses the possibility of highest plant work and efficiency in case of closed loop steam cooling while internal convection cooling has been found as the least effective cooling method. A gas turbine based cogeneration has been taken for study by Sanjay et al. [5].The research article investigates the effect of different gas turbine blade cooling on the discussed cycle. A. K. Mohapatra and Sanjay [6] studied the parametric study with variation in performance parameter such as TIT, compressor pressure ratio on a cooled gas turbine plant. Anupam Kumari and Sanjay [7] studied the effect of parameters affecting the exergetic and emission performance of basic and intercooled gas turbine cycles. The author advocates that inter-cooled gas turbine cycle should be preferred over basic cooled gas turbine cycle.

The present paper deals with the thermodynamic performance evaluation of basic gas turbine cycle incorporating air film cooling technique and internal convection cooling.

NOMENCLATURE

A	area (m^2)
C_p	specific heat at constant pressure ($\frac{kJ}{kg \cdot K}$)
C	Compressor
CC	combustion chamber
F_a	correction factor to account for the actual blade surface
h	specific enthalpy of the stream ($\frac{kJ}{kg}$)
$\bar{h}$	convective heat transfer coefficient ($w/m^2/K$)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (bar)
q	heat added (w)
r_{pc}	cycle pressure ratio
R	gas constant (kJ/kg-K)
S_g	blade perimeter (m)
St_{in}	average Stanton number
t	pitch of blade (m)
TIT	turbine inlet temperature (k)
W	specific work (kJ/kg)

SUBSCRIPTS

a	Air
b	Blade
cool	Coolant
f	Fuel
film	film cooling
g	Gas
GT	Gas turbine
in	Inlet
iso	Isothermal
j	Coolant bleed points
mech	Mechanical
p	Pressure
pt	Polytropic
Out	Outlet

GREEK SYMBOLS

α	Flow discharge angle
η	Efficiency (%)
ε	Heat exchanger effectiveness (%)
ξ	Coolant mass fraction

ACRONYMS

AFC	Air film cooling
C	Compressor
CC	Combustion chamber
GT	Gas turbine
ICC	Internal convection cooling
LHV	Lower heating value

II. SYSTEM CONFIGURATION

The above fig.1 represents the basic cooled gas turbine. The basic gas turbine cycle consists of an axial compressor, a combustion chamber and a gas turbine. The air is compressed in the compressor, which during compression is bled at the gas turbine blades. The fuel is burnt in the combustion chamber and after burning the expansion of flue gases takes place in gas turbine. In the gas turbine the mixing of bled air and flue gases, i.e. coolant and flue gases takes place in the turbine.

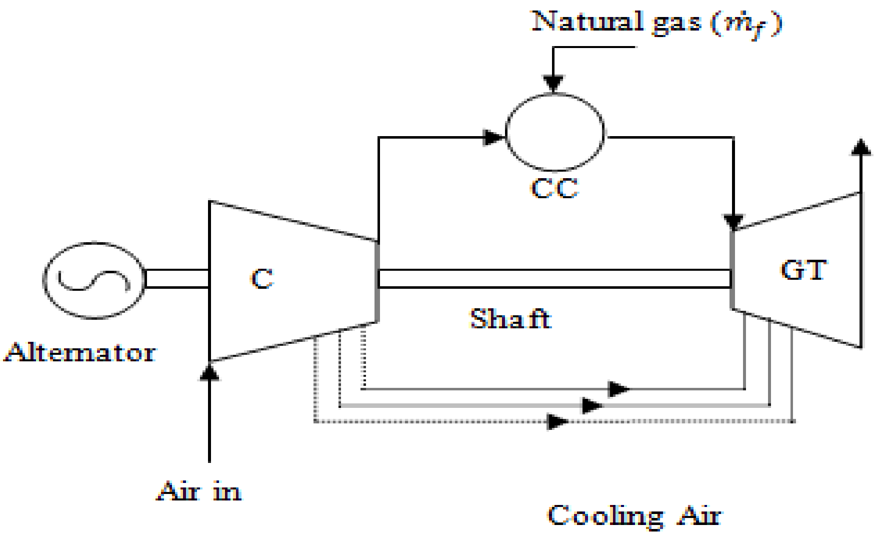

Figure 1 Basic cooled gas turbine

III. MODELING AND GOVERNING EQUATIONS

The thermodynamic model has been developed using energy and mass balance equations which are utilized to determine unknown state points in the cycle components.

Air Model

The specific heat of air has been modeled based on polynomial given by Touloukian and Tadash [8].

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

The specific heat of flue gas has been modeled based on polynomial given by Touloukian and Tadash [8]

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

Thus, the enthalpy of the flue gas and air can be calculated as under:

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

Compressor (C)

The temperature and pressure in the compressor is given by the equation

$$\frac{dT}{T} = \left(\frac{R}{\eta_{pt,c}\, c_{p,a}}\right)\frac{dp}{p} \quad (4)$$

The compressor work is given by

$$W_C = \dot{m}_e \cdot h_e + \sum \dot{m}_{cool,j} \cdot h_{cool,j} - \dot{m}_i \cdot h_i \quad (5)$$

Combustion Chamber (CC)

The mass balance of flue gases at the entry to the turbine is given by

$$\dot{m}_e = \dot{m}_i + \dot{m}_f \quad (6)$$

While energy balance at the combustor is given by

$$\dot{m}_f \cdot LHV \cdot \eta_{cc} = \dot{m}_e \cdot h_e - \dot{m}_i \cdot h_i \quad (7)$$

Mass of fuel required has been calculated using mass and energy balance of the combustion chamber

$$\dot{m}_f = \frac{[\dot{m}_e \cdot h_e - \dot{m}_i \cdot h_i]}{[\eta_{cc} \cdot LHV - h_e]} \quad (8)$$

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \quad (9)$$

Pressure at the inlet of gas turbine is given as:

$$p_{i,cc} = p_{e,c}(1 - \Delta p_{cc}) \quad (10)$$

Where $\Delta p_{cc} = 0.02$

Gas turbine (GT)

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

$$\frac{dT_g}{T_g} = \left[\left(\frac{p+dp}{p}\right)^{\frac{R.\eta_{pt}}{c_{p,g}}} - 1\right] \quad (11)$$

Now gas turbine work is given by the equation

$$W_{GT} = \left(\dot{m}_i h_i + \sum \dot{m}_{cool,j} h_{cool,j} - \dot{m}_e h_e\right) * \eta_{mech} \quad (12)$$

Also the net specific work is given by the equation

$$W_{net} = W_{GT} - W_C \quad (13)$$

The cycle efficiency is given by

$$\eta_{GT} = \frac{W_{GT,net}}{Q} = \frac{W_{GT,net}}{\dot{m}_f.LHV} \quad (14)$$

Cooled gas turbine model

Air Film cooling (AFC)

A simple model of film cooling is shown in Fig. 3. The hot gases ($\dot{m}_g$) passes over the blade surface, while the coolant ($\dot{m}_{cool}$) passing internally throughthe blades channels is ejected out from the leading edge which forms a film over the blade surface and finally mixes with hot gas at the trailing edge. The film so formed reduces heat transfer from hot gas to the blades.

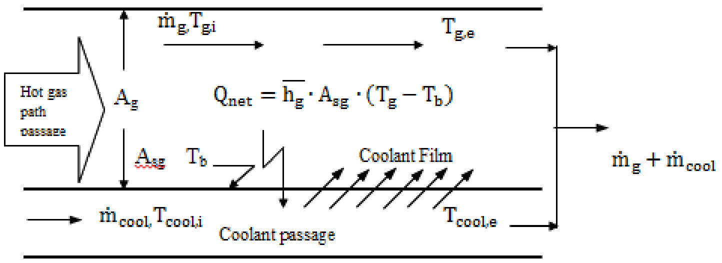

Figure 2 Model of air film cooling of turbine blade

The mass flow rate of coolant air bled (ζ) is given by:

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

Internal convection cooling: A simple model for internal convection cooling is shown in fig. the hot gases passes over the blade surface of intricate shapes in case of internal convection cooling (ICC), while coolant comes out from the tip of the blades.

The mass flow rate of coolant air bled (ζ) is given by:

$$\zeta = \frac{\dot{m}_{cool}}{\dot{m}_g} = \frac{St_i \cdot S_g}{\varepsilon_{cool} \cdot t \cdot \cos\alpha} * \frac{c_{pg}(T_{g,i}-T_b)}{c_{p,cool}(T_b-T_{cool,i})} * F_{sa} \tag{16}$$

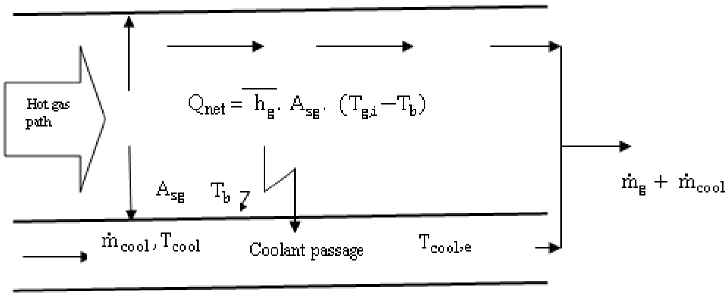

Figure 3 Model for internal convection cooling of turbine blade

IV. RESULT AND DISCUSSION

The above fig.4 represents the variation of coolant mass fraction of air film cooled blade (AFC) and internal convective cooled blades (ICC) with TIT. The above fig. clearly indicates that coolant mass flow rate increases in both the cooling techniques but a little sharply in case of convectively cooled blades. This variation shows a good agreement with the previously published papers. The coolant mass flow requirement is finding to be more in comparison to film cooled blades. This happens because as TIT is increased the more amount of coolant is required to cool more number of stages.

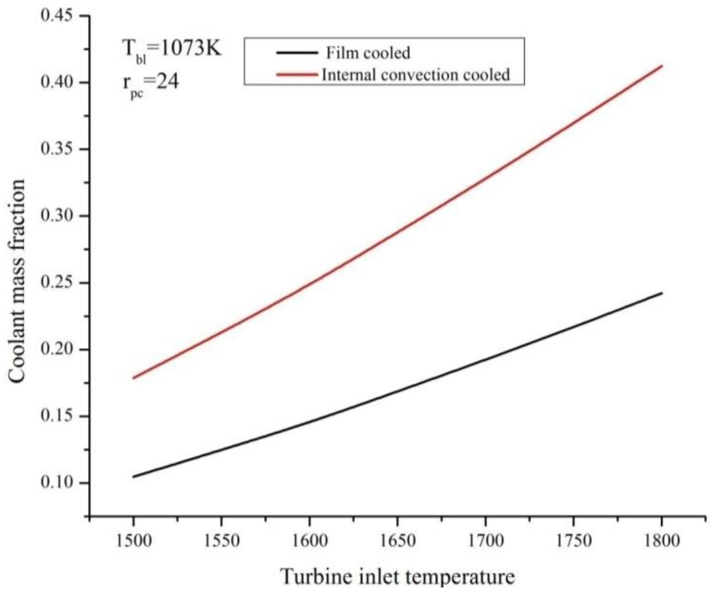

Figure 4 Variation of coolant mass flow rate with TIT

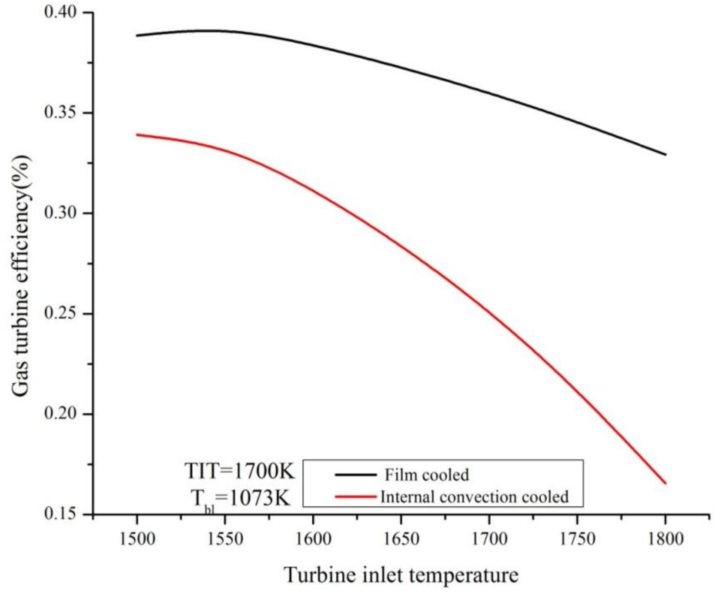

Figure 5 Variation of gas turbine efficiency flow rate with TIT

The above diagram explains the behavior of gas turbine efficiency with TIT. The study has been carried out at the blade temperature of 1073K and TIT of 1700K. It can be clearly depicts from the above diagram that efficiency of the cycles i.e. film cooled and convective cooled cycles increases initially and again it starts decreasing. The efficiency of the air film cooled (AFC) cycle is greater as compared to convective cooled cycle. The reason for this is the lower mass flow rate for the film cooled cycle as comparison to convective cooled cycle. The higher mass flow rate requirement causes more amount of losses i.e. mixing losses, cooling losses etc.

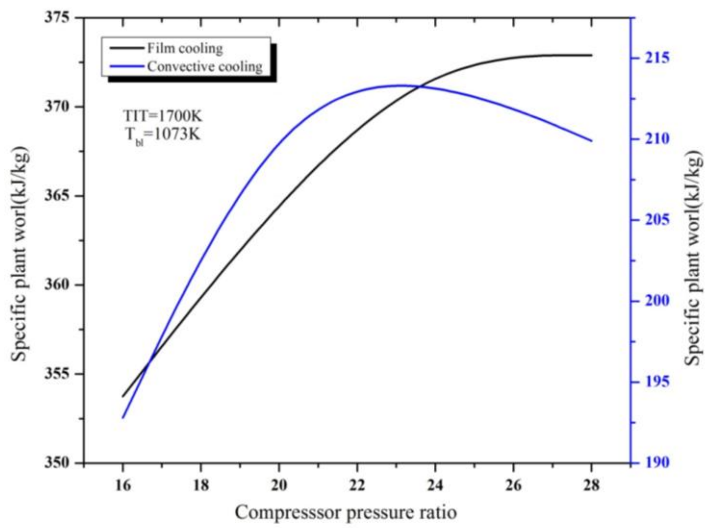

Figure 7 Variation of gas turbine specific work with compressor pressure ratio

The above fig.7.gives the picture of variation of specific work output of gas turbine plant for both air film cooled (AFC) and internal convective cooled (ICC) techniques, with variation in compressor pressure ratio. The specific work output for the film as well as convective cooled blades has been found to be of increasing nature with increase in compressor pressure ratio. The diagram clearly indicates that Specific plant output for the film cooled blade is more in comparison to convectively cooled blades.

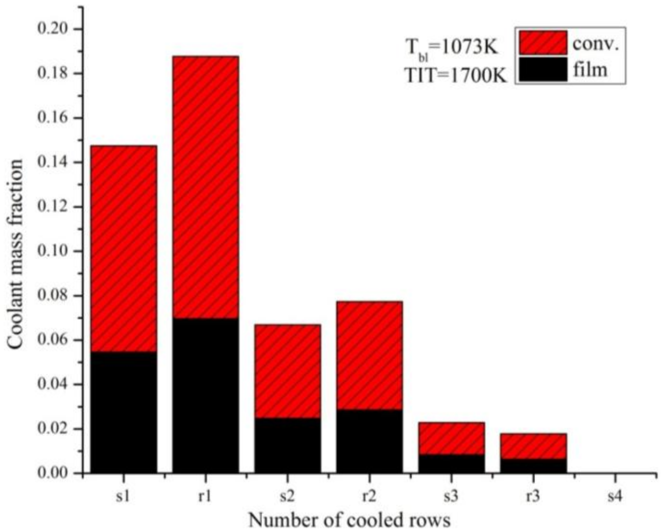

Figure 8 Variation of coolant mass flow rate with number of cooled rows

The fig.8.represented above is the representation of coolant mass flow requirement with total number of cooled rows required for gas turbine blade cooling. The result have been plotted at a blade temperature of 1073K and TIT of 1700K, for the coolant mass flow rate required for the blade cooling employing film cooling as well as convective cooling techniques. The fig clearly indicates that the coolant mass flow requirement is greater in case of convective cooling techniques as compared to film cooling techniques.

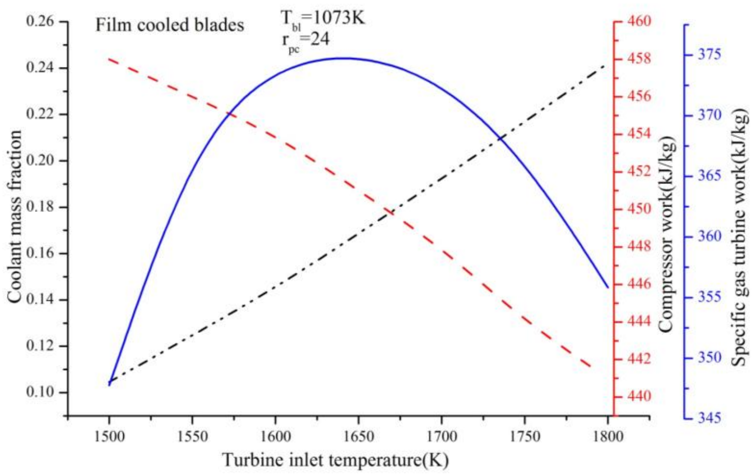

Figure 9 Performance analysis of air film cooled blades with TIT

The fig.9.represented above shows the variation of coolant mass flow requirement, compressor work input and gas turbine net-work output for the air film cooling techniques, against TIT. The result has been plotted at a blade temperature of 1073K and TIT of 1700K. The fig. depicts that as the TIT is increased the coolant mass flow requirement is also increased this is because of more number of stages to get cooled at higher TIT. The work input to compressor shows a decline trend with increase in TIT as now lesser amount of coolant is to be compressed as TIT value is increased. The specific work output for the gas turbine plant shows an increasing and decreasing trend with increasing value of TIT.

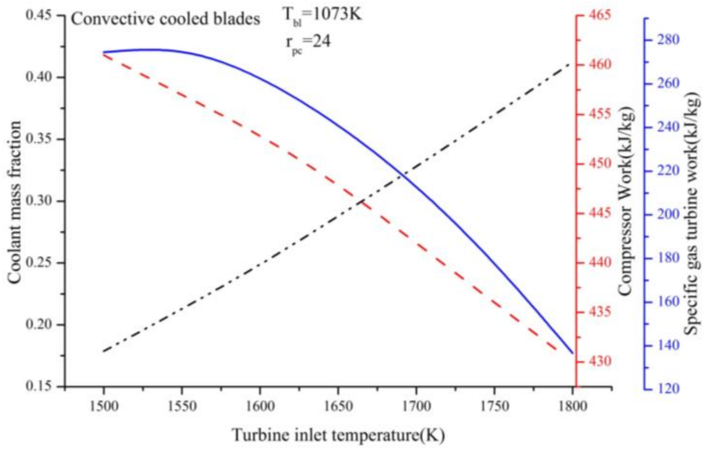

Figure 10 Performance analysis of internal convection cooled blades with TIT

The fig.10 above represented shows the variation of coolant mass flow requirement, compressor work input and gas turbine net-work output for the air internal convection cooling techniques, against TIT. The result has been plotted at a blade temperature of 1073K and TIT of 1700K. The fig depicts that as the TIT is increased the coolant mass flow requirement is also increased this is because of more number of stages to get cooled at higher TIT. The work input to compressor shows a decline trend with increase in TIT as now more amount of coolant is to be bled from compressor and a lesser amount of coolant is to be compressed as TIT value is increased. The specific work output for the gas turbine plant shows an increasing and decreasing trend with increasing value of TIT.

VI. CONCLUSION

(i) The film cooling technique offers the lesser amount of coolant mass flow requirement as comparison to convective cooling technique for a gas turbine plant.

(ii) The thermal efficiency gas turbine plant employing film cooled blades has been found to be better as compared to convective cooled blades.

(iii) The specific gas turbine work output has been found to be greater for air film cooing technique as compared to air internal convection cooling technique.

(iv) The row-wise coolant mass flow requirement has been encountered greater for air film cooled technique in comparison to convective cooled blades.

(v) At a fixed value of turbine blade temperature and compressor ratio, the value of coolant mass flow requirement and specific plant work increases for both the cooling techniques i.e. film cooling s well as convective cooling techniques.

(vi) The compressor work shows a decline trend for both film as well as convective cooling techniques.

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