Thermodynamic Evaluation of Gas/Steam Combined Cycle Performance With Active Controlled Film Cooling

Sanjay Kumar and Onkar Singh

ABSTRACT

Efficiency of gas turbine cycles can be improved by increasing the turbine inlet temperature. Advanced gas turbines operate at temperatures far above their material limitations to increase thermal efficiency. So, film cooling technique is mostly used to protect the gas turbine blades from high temperature gases. The film cooling jets penetrate into the mainstream gas and form a thin film for protecting the blade surfaces from hot gas. However, due to lift-off effect the attachment of the coolant jet to the blade wall, downstream, becomes crucial. Plasma actuator strategy proposed by some of the researchers may be considered to be utilized, to maintain the attachment of jet with the blade-wall and improve the film cooling effectiveness. In this article the effect of a proposed active controlled film cooling technique using plasma actuator strategy on thermodynamic performance of gas/steam combined cycle has been evaluated and compared with the combined cycle employing simple film cooling technique as well as with advanced transpiration cooling technique of gas turbine blades. Reduced coolant requirement and hence reduced dilution losses with active controlled film cooling as compared to simple film cooling, results in improved topping as well as bottoming cycle performance. It is seen that the combined cycle efficiency with active film cooling is comparable to the transpiration cooled combined cycle efficiency. At a turbine inlet temperature (TIT) of 1900 K, the combined cycle efficiency with active film cooling strategy is higher by 0.5% than that with simple film cooling.

Keywords: active film cooling strategy, gas/steam combined cycle performance, transpiration cooling

NOTATION

c_p	specific heat at constant pressure (kJ/kg-K)
$\dot{m}$	mass flow rate (kg/s)
St	Stanton number
T	temperature (K)
TIT	turbine inlet temperature (K)

Greek symbols

ε	effectiveness
η	efficiency (%)
λ	ratio of cooled surface area to hot gas flow cross sectional area
θ	deaerator temperature ratio

Subscripts

aw	adiabatic wall
b	blade
c	coolant, cooling
g	gas
i	inlet

INTRODUCTION

Modern gas turbines employ sophisticated cooling techniques to thermally protect the turbine blades from extreme environments. These techniques include actively cooling the components with relatively cooler air as well as passively protecting the system by improving the material durability of the components. Traditionally various internal and external cooling techniques are employed to bring down the temperature of the blade material below its melting point. In internal cooling also called convection cooling, relatively cold air is bypassed from the compressor and passed through the hollow passages inside the turbine blade. In external cooling, the bypassed air is passed out through small holes at discrete locations of the turbine blade. This relatively cold air creates a protective blanket that protects the turbine blade from the harsh environment. This type of cooling is called film cooling (Figure 1). In film cooling, a secondary coolant usually cool air bled from the compressor stage is ducted through the interior of the blade and injected into the blade boundary layer through a series of holes. The mainstream flow around the blades causes this injected coolant flow to bend and create a thin, cool, insulating layer of coolant, protecting the external surface of the blade from hot gases.

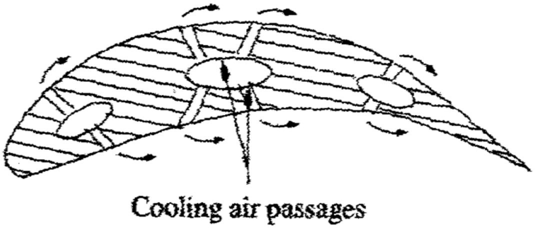

Figure 1. Film Cooling of Gas Turbine Blade

Transpiration cooling is another type of external cooling technique in which the coolant is ejected out from a blade surface having large number of smaller holes and completely shrouds the blade surface by formation of a large number of small conjoint films of coolant all along the blade surface, so the cooling effectiveness is better. The heated coolant at the film surface is transported downstream by the momentum of the hot gas flow, continuously replaced with fresh coolant flowing out of the wall.

Among different cooling techniques available, the convection and film cooling are the most widely used techniques. The advances in turbine inlet temperature with different blade cooling techniques e.g. convection, film and transpiration cooling techniques have been discussed by many researchers e.g. Najjar, Y,S,H, (2004), Sanjay et al. (2008), Sanjay and Singh, O. (2008), Horlock et al. (2001) and Polejhaev (1997).

In case of film cooling the cooling effectiveness is limited by the loss of flow attachment just downstream of the cooling hole and formation of vortices which allow the hot gas to penetrate to the wall. To maintain the jet attachment, Wang and Roy (2009) proposed the concept of an active cooling method i.e. horseshoe plasma actuator at the downstream of the cooling hole. The active cooling methods including Plasma actuator strategy are beneficial for film cooling cases with badly separated jets. Though in this arrangement there could be practical considerations like surface oxidation of the electrodes etc. In transpiration cooling technique the blade is almost porous i.e. the coolant is ejected out from a large number of holes like perforation and completely shrouds the blade surface by formation of small conjoint films of coolant all along the blade surface and the problem of coolant jet attachment with the blade surface is not realized in this cooling techniques as with the film cooling technique. The present study evaluates the impact of active controlled cooling i.e. horseshow plasma actuator technique combined with film cooling on thermodynamic performance of gas/steam combined cycle. The results obtained so have been compared with the performance results of cycle comprising of simple film cooling technique as well as advanced transpiration cooling technique.

FILM ACTIVE COOLING STRATEGY

In film cooling technique the cooling effectiveness is limited by the loss of flow attachment just downstream of the cooling hole and formation of vortices which allow the hot gas to penetrate to the wall. To maintain the jet attachment, Wang and Roy (2009) proposed the concept of an active cooling strategy i.e. horseshow plasma actuator at the downstream of the cooling hole. The proposed concept consists of a set of electrode pairs at the downstream of the cooling hole, between which electric potential and induced weak ionization of the working gas generate an electric body force which is dominant inside the boundary layer. According to Wang and Roy (2009), with active cooling arrangement the film cooling effectiveness is claimed to increase by 100% though this arrangement will utilize about 1% of turbine power, which may reduce the output for more effective cooling. To assess the impact of film cooling combined with active cooling strategy, the film cooling effectiveness is assumed as 0.8 (100% increased value of the normal average effectiveness value of 0.4 as indicated in Horlock et al. (2001), and the gas turbine power output is assumed to be reduced by 1% in the present study.

The coolant requirement for film cooling of gas turbine blades is given by equation as described by Sanjay and Singh, O, (2008)

$$\frac{\dot{m}_c}{\dot{m}_g} = \lambda.St_g.\left(\frac{c_{p,g}}{c_{p,c}}.\right)\frac{\left(T_g - T_b\right) - \varepsilon_{aw}[T_g - \{T_{c,i} + \eta_c(T_b - T_{c,i})\}]}{\eta_c(T_b - T_{c,i})} \qquad (1)$$

where, 'λ' is the ratio of cooled blade surface area to mainstream flow area.

The coolant requirement for transpiration cooling of gas turbine blades is found by following equation as described by Kumar, S. and Singh, O. (2010).

$$\frac{\dot{m}_c}{\dot{m}_g} = \lambda \cdot St_g \cdot \ln . \left[\begin{array}{l} \dfrac{c_{p,g}}{c_{p,c}} \cdot \dfrac{1}{\eta_c \cdot (T_b - T_{c,i})} \Big[(T_g - T_b) - \varepsilon_{aw} \\ \qquad \times \left\{ T_g - \left(\eta_c \left(T_b - T_{c,i} \right) + T_{c,i} \right) \right\} \Big] + 1 \end{array} \right] \tag{2}$$

For cooling of gas turbine blades a fraction of the compressed air is bled from the compressor. The considered combined cycle is comprises of a simple gas turbine cycle consisting of an advanced four-stage gas turbine and a steam cycle consisting of a dual pressure HRSG. For the advanced four-stage gas turbine considered here, the cycle efficiency of the cooled gas turbine is calculated by using mass and energy balance as described in details in author's previous work i.e. Kumar, S. and Singh, O. (2010). Considering adiabatic mixing of coolant and main flow the mixture properties i.e. temperature, specific heat, enthalpy etc are determined as function of temperature and composition of mixed gas as described in Kumar, S. and Singh, O. (2011). The combined cycle performance is calculated as described in author's previous work i.e. Kumar, S. and Singh, O. (2012).

RESULTS AND ANALYSIS

The performance evaluation of simple gas turbine cycle and combined gas/steam cycle using active cooling strategy has been carried out for pressure ratio of 23 and other gas turbine cycle input parameters given in Table 1 and steam cycle parameters given in Table 2 and plotted accordingly.

Figure 2 compares the coolant requirement for active cooling method combined with film, with other cooling techniques i.e. film cooling and with transpiration cooling respectively with varying TIT. It is observed that the coolant requirement increases with increase in TIT for each of three cases. Cooling requirement with active cooling method combined with film cooling is significantly less even than by transpiration cooling technique due to increased cooling effectiveness. Due to reduced coolant requirement the dilution losses are also reduced and the

Table 1: Gas Turbine Cycle Performance Input Parameters

Ambient temperature	: 15^{o}C
Ambient pressure	: 1.013 bar
Relative humidity	: 60%
Dry air composition by volume percentage	: N_2: 78.09%, O_2: 20.95%,
	Ar: 0.93%, CO_2: 0.03%
Compressor polytropic efficiency (ηp,cmp)	: 90 %
Pressure loss in air filter at compressor inlet	: 0.01 bar
Combustor efficiency (ηcc)	: 99.1%
Pressure loss in combustion chamber	: 3 % of entry pressure
Turbine polytropic efficiency (ηp,gt)	: 89 %
Mechanical efficiency (ηmech)	: 98.7 %
Gas turbine exhaust pressure loss	: 0.02 bar
Natural gas composition by volume percentage:	: CH_4 = 90.00%; C_2H_6 = 4.50%;
LHV of natural gas	N_2 = 4.00%; CO_2 = 1.50%;
Mainstream Reynolds number in gas turbine	: 44,769 kJ/kg
Prandtle number of mainstream gas	: $1.6x10^6$
Allowable blade material temperature (Tbl)	: 0.7
Average adiabatic wall film effectiveness (εaw)	:1073 K
	: 0.4

Sources: Najjar, Y.S.H. et.al. (2004), Sanjay et al. (2008), Horlock et al. (2001), Kumar and Singh (2010), Chiesa and Macchi (2004)

topping cycle efficiency with active film cooling also increases significantly in comparison to that with simple film cooling. However the consumption of about 1% of gas turbine power for active cooling limits the increase of cycle efficiency and the cycle efficiency with active film cooling approaches to the transpiration cooled cycle efficiency. As shown in Figure 2 at a TIT of 1800 K the active film cooled cycle efficiency is higher by 0.45% than simple film cooled cycle efficiency and at a TIT of 1900 K the active film cooled cycle efficiency is higher by 0.5% than simple film cooled cycle efficiency.

Figure 2 compares the topping cycle exhaust temperature for active cooling method combined with film cooling, with other cooling techniques i.e. film cooling and with transpiration cooling respectively with varying TIT. It is observed that the exhaust temperature increases with increase in TIT for each of three cases. The exhaust temperature with active cooling method combined with film cooling is highest due to re-

Table 2: Steam Cycle Input Parameters,

Pressure loss in air filter at compressor inlet	: 0.01 bar
Combustor efficiency (ηcc)	: 99.1%
Pressure loss in combustion chamber	: 3 % of entry pressure
Turbine polytropic efficiency (ηp,gt)	: 89 %
Mechanical efficiency (ηmech)	: 98.7 %
Gas turbine exhaust pressure loss	: 0.02 bar
Natural gas composition by volume percentage:	: CH_4 = 90.00%; C_2H_6 = 4.50%;
LHV of natural gas	N_2 = 4.00%; CO_2 = 1.50%;
Mainstream Reynolds number in gas turbine	: 44,769 kJ/kg
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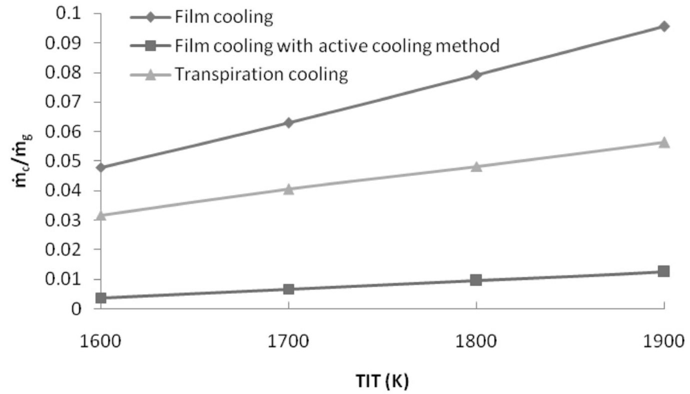

Figure 2. Effect of active cooling method on coolant requirement with varying TIT

duced coolant requirement and hence reduced dilution losses. Higher gas temperature with active film cooling method results in improved bottoming cycle performance and its effect is visible in Figure 4, which shows that combined cycle efficiency with active film cooling is higher than simple film cooled cycle, and is slightly above the transpiration cooled combined cycle efficiency.

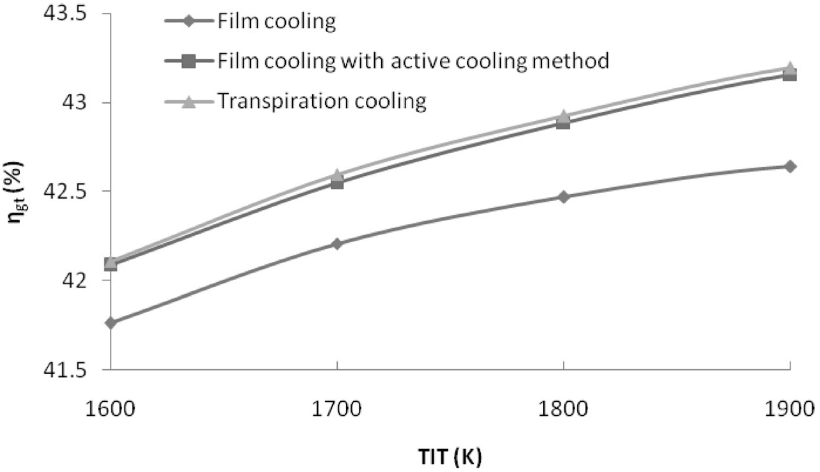

Figure 3. Effect of active cooling method on topping cycle efficiency with varying TIT

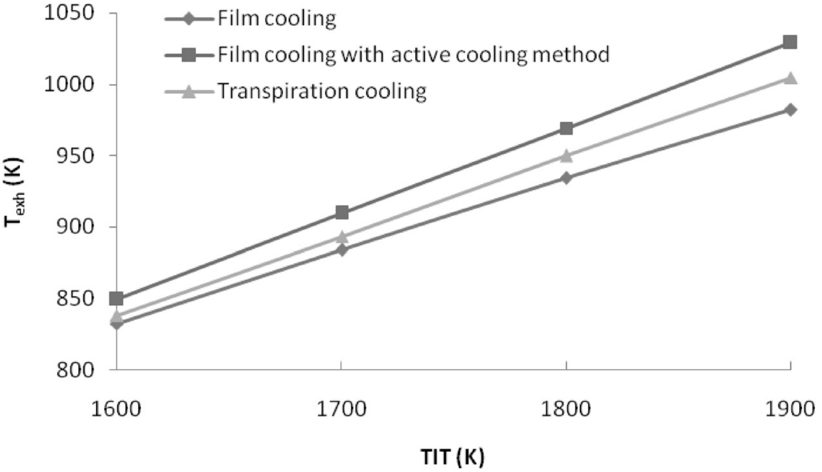

Figure 4. Effect of active cooling on gas turbine exhaust temperature with varying TIT

Figure 5 compares the topping cycle net specific work for active cooling method combined with film cooling, with other cooling techniques i.e. film cooling and with transpiration cooling respectively with varying TIT. It is seen that the net specific work of gas turbine cycle

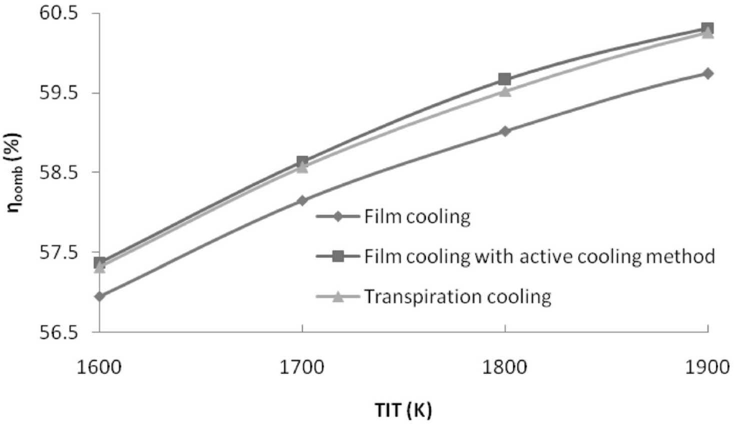

Figure 5. Effect of active cooling on combined cycle efficiency with varying TIT

increases with increase in TIT for each of three cases. The topping cycle net specific work output with active cooling method combined with film cooling is higher than for that with transpiration cooling. This is attributed to reduced coolant requirement and hence reduced dilution losses in gas turbine. Also due to reduced cooling air requirement, comparatively more compressed air is available for combustion and further expansion in gas turbine. The combined cycle net specific work output is also improved with active cooling method combined with film cooling as seen in Figure 6.

CONCLUSION

The performance of the simple gas turbine cycle as well as that of combined cycle employing film cooling combined with active cooling strategy are compared with the cycle performance employing simple film cooling and transpiration cooling respectively with varying TIT. The coolant requirement increases with increase in TIT for each of three cooling methods. Cooling requirement with active cooling method combined with film cooling is significantly less even than by transpiration cooling technique due to increased cooling effectiveness. Due to reduced coolant requirement the dilution losses are also reduced and the topping

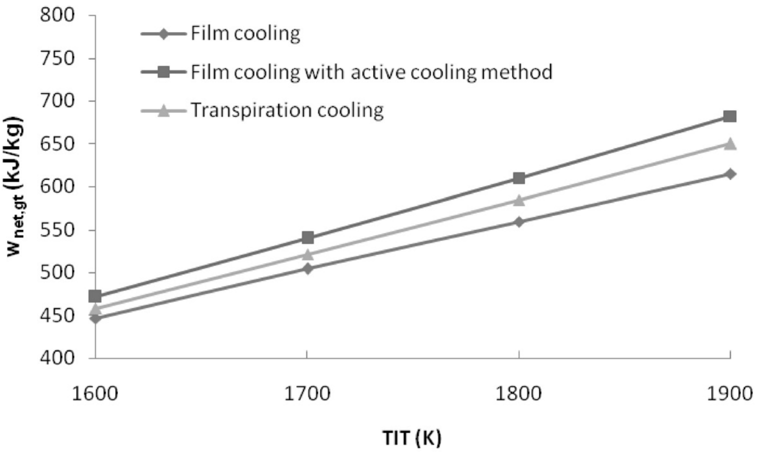

Figure 6. Effect of active cooling on topping cycle net sp. work with varying TIT

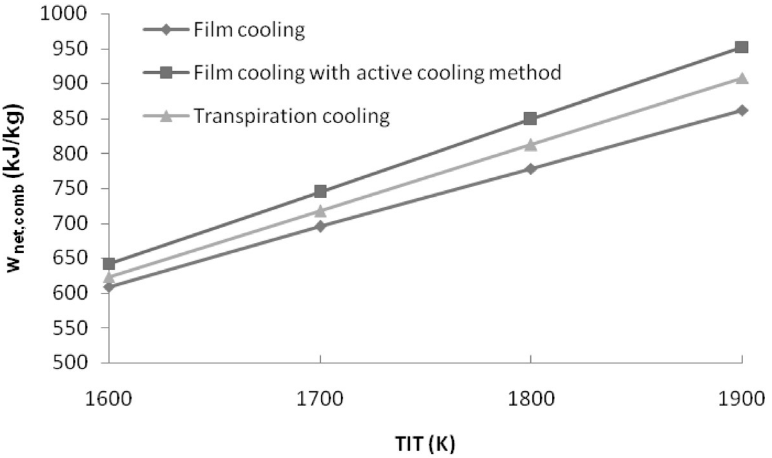

Figure 7. Effect of active cooling on combined cycle net sp. work with varying TIT

cycle efficiency with active film cooling also increases significantly in comparison to that with simple film cooling. However the consumption of about 1% of gas turbine power for active cooling limits the increase of cycle efficiency and the cycle efficiency in case of active film cooling approaches to the transpiration cooled cycle efficiency.

The topping cycle exhaust temperature increases with increase in TIT for each of three cases. The exhaust temperature with active cooling method combined with film cooling is highest due to reduced coolant requirement and hence reduced dilution losses. Higher gas temperature with active film cooling method results in improved bottoming cycle performance and hence the combined cycle efficiency with active film cooling is higher than simple film cooled cycle efficiency and is slightly above the transpiration cooled combined cycle efficiency. At a TIT of 1900 K the combined cycle efficiency with active film cooling strategy is higher by 0.5% than that with simple film cooling.

The topping cycle as well as combined cycle net specific work output in case of active cooling method combined with film cooling is higher than for that with transpiration cooling. This is attributed to reduced coolant requirement and hence reduced dilution losses in gas turbine. Also due to reduced cooling air requirement, comparatively more compressed air is available for combustion and further expansion in gas turbine.

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