Thermodynamic Evaluation of Advanced Combined Cycle Burning Hydrogen

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Abstract

The present work deals with the thermodynamic evaluation of gas turbine based combined cycle using the latest gas turbine e.g ABB GT26 gas turbine (advanced) burning hydrogen rich fuel. The bottoming cycle is also similar to the traditional HRSG based steam generation system. The proposed cycle burns hydrogen and the gas turbine exhaust gas generates steam in HRSG is allowed to expand in a separate steam turbine upto condenser pressure.

The gas turbine (ABB GT26) is reheat type and the blade cooling is done by air bled from compressor. The same turbine is subjected to closed loop steam cooling. Parametric study has been performed on plant efficiency and specific work for various independent parameters such as TIT, $r_{p,c}$, $r_{p,hpt}$, RIT, blade temperature etc. It is observed that due to higher compressor pressure ratio involved in reheat gas turbine combined cycle and higher temperature of exhaust, the plant efficiency and specific work are higher with the advanced reheat gas/steam combined cycle over the simple combined cycle, The effect of hydrogen fuel instead of traditional NG is significant on cycle performance. Steam cooling offers better performance over air-cooling.

Introduction

Fuels derived from fossil sources will continue to play a major role in global energy supply in the near future. However, fossil fuels are the major source of Green-house gases like CO_2. In light of the Nobel Peace Price awarded jointly to inter-Governmental Panel on Climate Control (IPCC) and US ex-vice-president Al-Gore for 2007 the chances are very bright that attention will shift to reduction and thereafter elimination of GHG from power generation.

In the last few years the great attention addressed to the greenhouse effect, has prompted the analysis of potential zero-emission power plants, by using hydrogen as fuel. Also with improvement to combustion technology other potential zero-emission power plants burning oxygen and any other hydrocarbon in order to produce a working fluid, composed of steam and carbon dioxide, at high temperature and high pressure, which can power conventional or advanced turbines. With improvements in carbon capture and turbine technology, efficiencies in the range of 50% are possible with nearly 100% carbon capture, thus providing a stiff challenge to the potential of hydrogen burning turbines. But hydrogen and electricity may become the favored twin energy carriers in a possible "greenhouse driven" future due to their lack of CO_2 emissions at the point of use. For this reason, in the technical works it is possible to find many examples of cycles based on hydrogen combustion; moreover if oxygen is used as oxidizer, it is possible to obtain semi-closed cycles where the working fluid is H_2O. These cycles seem to have great thermodynamic potentialities, but in these analyses it is very important to adopt some reasonable assumptions. In fact, by choosing very high values for the maximum pressure and temperature and neglecting the energy requirements for the compression and the production of oxygen and, these cycles can attain high efficiency 65–70%

In this study thermodynamic evaluation of combined cycle with reheat in gas turbine using the latest gas turbine (Alstom GT26) burning hydrogen rich fuel has been attempted. This actual turbine is air-cooled. The study has been extended to consider it as closed loop steam cooled. The bottoming cycle is triple pressure system with reheat. For evaluating the performance, mathematical modeling of various elements of combined cycle has been used for real situation. Parametric study has been carried out on plant efficiency and specific work for various independent parameters such as turbine inlet temperature, compressor pressure ratio, gas turbine reheating pressure ratio, reheater inlet temperature and turbine blade temperature, etc.

In Japan a development program called WE-NET that is nearly complete has conceptualized and developed a cycle burning pure hydrogen with pure oxygen and expanding the resulting fluid i.e. steam at high pressure and temperature in a Rankine cycle type expander with great success. In the US a separate development program named Advanced Hydrogen Turbine Development program expected to run through year 2012 is in progress. Significant work has been done by many researchers in this area. M. Gambini et al., Wen-Ching Yang, Naoyuki Kayukawa, A. D. Rao et al. have done pioneering work in this area.

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System Configuration

Topping (Reheat Gas Turbine) and Bottoming Cycle Fig. 1 shows the schematic of ABB GT26 gas turbine cycle in which reheating of HP exhaust gas is done in a second combustor and the reheated gas expands in IP/LP turbine. The compressor pressure ratio is 30 and turbine exhaust temperature is 913K. The exhaust mass flow rate is 562 kg/s, net efficiency (LHV) is 38.23% and net power output is 262 MW at ISO conditions. This turbine has been chosen as a reference cycle. The turbine is cooled by air (film cooling) bled from compressor. The same turbine burning hydrogen-blended natural gas is subjected to closed loop steam cooling and the effect of this observed on the performance. Ten percent hydrogen (by weight) is blended with natural gas in the proposed cycle. Pure oxygen has to be introduced in the combustor so as to ensure complete combustion of hydrogen.

NOMENCLATURE

C=compressor
cc= combustion chamber
c_p = specific heat at constant pressure, (kJ/kg.K)
F_{sa}= correction factor for gas turbine blade surface area
HPT=high pressure turbine
IPT= intermediate pressure turbine
LPT= low pressure turbine
HRSG= heat recovery steam generator
PP= pinch point
Q=heat transfer rate, (kJ/kg.sec)
m = mass flow rate of air, (kg/sec)
r_{pc} = compressor pressure ratio
RIT= reheat inlet temperature in topping cycle
Sg= blade perimeter
St = Average Stanton number at inlet condition
T= temperature, (K)
TIT= turbine inlet temperature in topping cycle, (K)
t= pitch of blades
W_{plant} = plant specific work, (kJ/kg)
α =inlet flow discharge angle, (θ)
ε =effectiveness
$(\eta_{iso})_{film}$= isothermal effectiveness for film cooling
η = efficiency, (percentage)
NG= natural gas

Suffixes

bl= blade surface
c= coolant
D/A= deaerator
in= inlet
g= gas
HP= high pressure
IP= intermediate pressure
LP= low pressure
o = stagnation value
out= outlet
RH=reheat

The combustion chamber has to be modified suitable to burn hydrogen-blended natural gas. The blending of hydrogen with natural gas is done in a suitable mixer. For complete combustion of blended hydrogen, pure oxygen may be required so as to achieve its complete combustion. At turbine startup the gas turbine is run on natural gas until the turbine operation has stabilized. Subsequently hydrogen-blended natural gas is introduced for burning.

The bottoming cycle is a triple pressure reheat (3PR) system (fig. 2) in each case. T-s diagram for combined cycle is shown in fig. 3 while T-Q diagram for the heat recovery steam generator (HRSG) is given in fig. 4. The cooling steam is taken from the exhaust of high pressure steam turbine and while cooling the gas turbine, coolant steam is superheated which is mixed with the superheated steam coming out from the HRSG and finally fed to IP turbine for expansion, The input data for the combined cycle is given in Table 1.

Blade Cooling Model

In order to maintain the surfaces of turbine blades exposed to hot gas below a certain safe working temperature, blades are cooled by internal convection, film and transpiration mechanism employing different cooling medium such as air, water and steam. The cooling model used in this study is a refined version of Louis, et al. [1983]. The simple model for internal convection and film cooling (open loop) is given in fig. 5. The model assumes the cooling blade channel as heat exchanger operating at constant

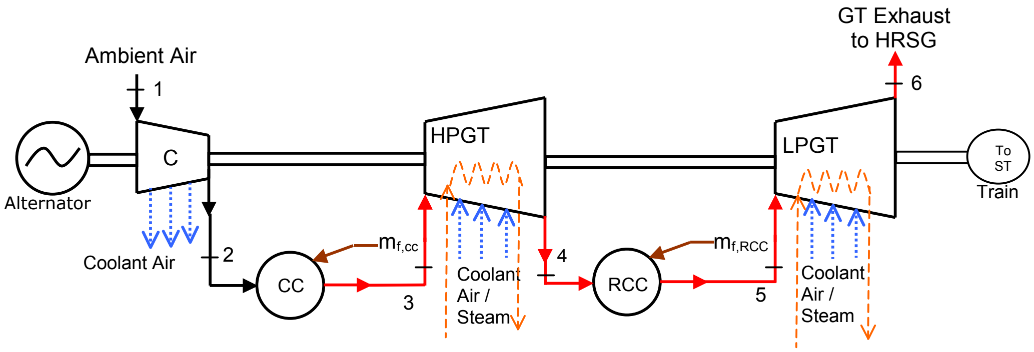

Fig. 1 Schematic of a reheated gas turbine

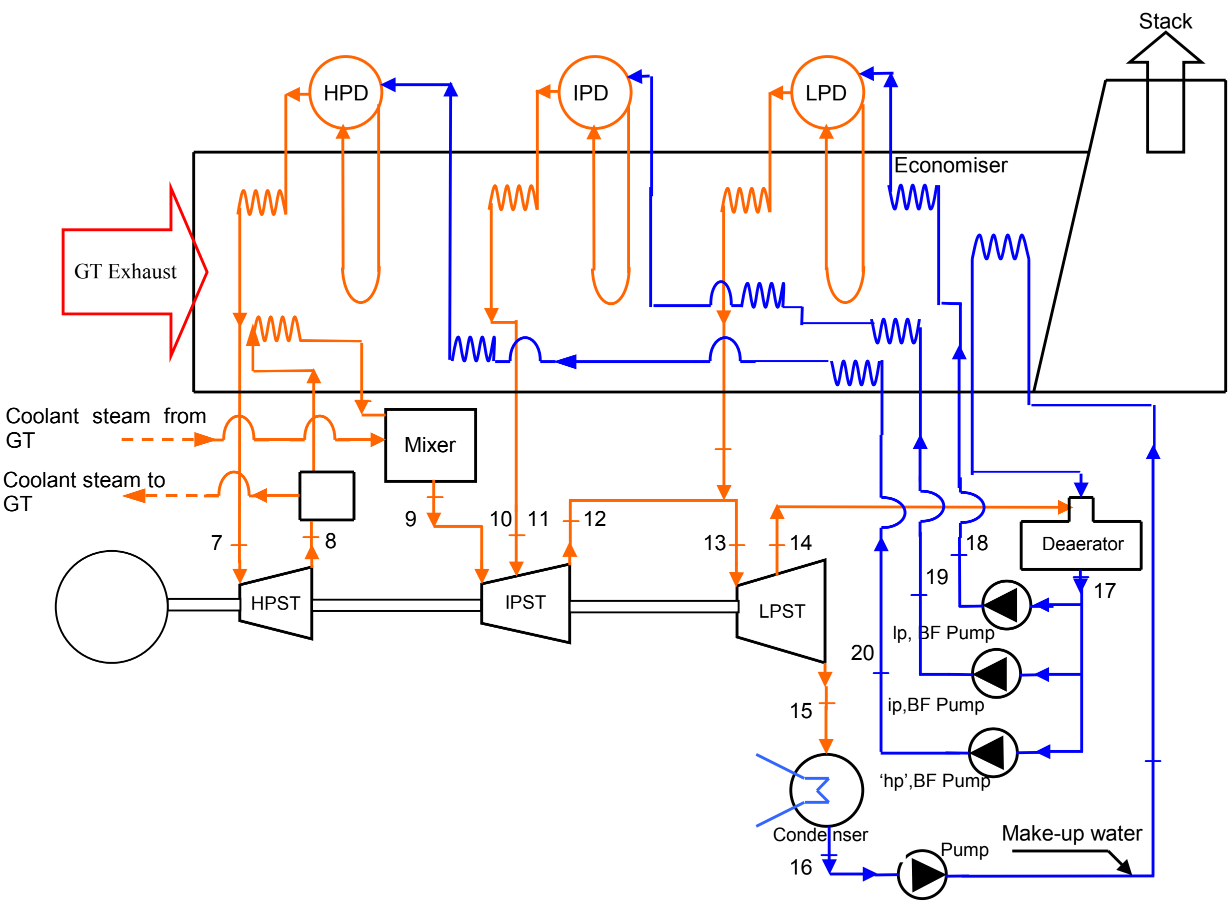

Fig. 2. Schematic of a triple pressure reheat steam cycle (3PR) configuration

temperature and the coolant exit temperature is expressed as a function of heat exchanger effectiveness, ε. A concept of isothermal

The mass flow rate of cooling fluid required in a blade row is given by the following expression

$$\frac{m_c}{m_g} = \left[1-(\eta_{iso})_{film}\right] \times \left[\frac{St_g \cdot c_{pg}}{\varepsilon \cdot c_{pc}}\right] \times \left[\frac{S_g \cdot F_{sa}}{t \cdot \cos\alpha}\right] \times \left[\frac{T_{og,in} - T_{o,bl}}{T_{o,bl} - T_{o,cin}}\right]$$

Here, ε =0.4, for film cooling, $(\eta_{iso})_{film}$ =0.4 and for convection ,$(\eta_{iso})_{film}$=0.0 , $S_g/t\cos\alpha$ =3.0 and $T_{o,bl}$=1123K, St_g=0.005.

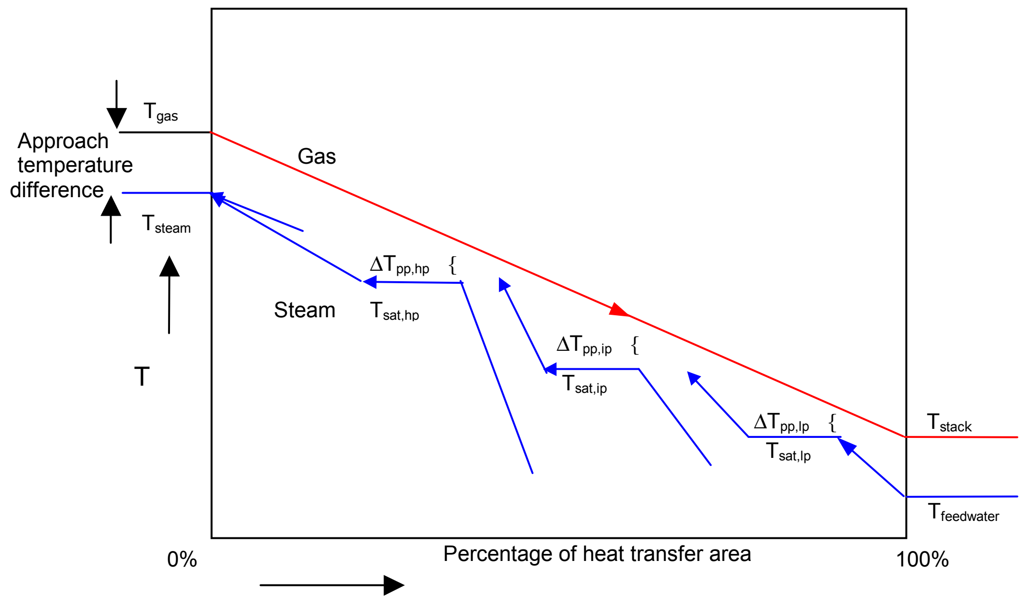

Fig. 3 T-Q diagram of a triple pressure reheat HRSG/ steam cycle (3PR) configuration

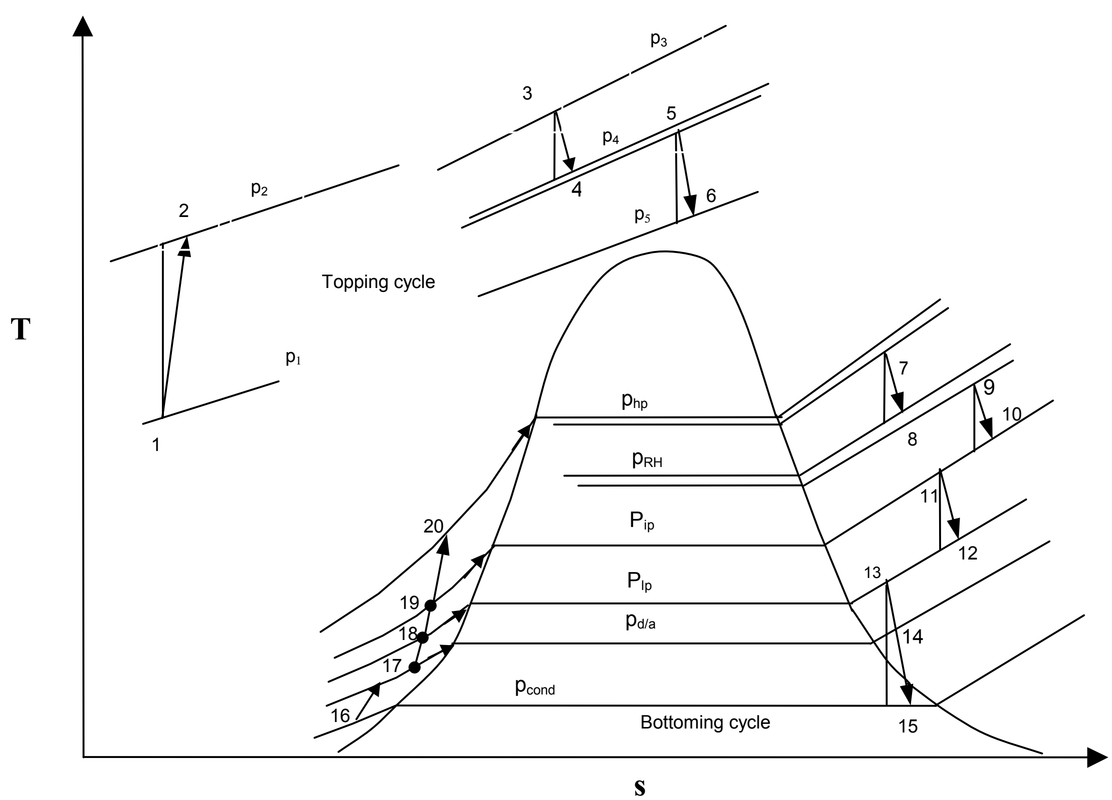

Fig. 4 Temperature-entropy (T-s) representation of a reheat gas, triple pressure reheat steam cycle (R3PR) configuration

The open loop cooling offers cooling and mixing losses while closed loop cooling only offers cooling loss of lower magnitude. The cooling loss in a row of blades results in a drop of stagnation temperature at constant pressure which is assumed to take place at the exit of cooled row. The mixing of coolant with primary flow causes stagnation pressure drop which is considered to take place at the exit of cooled row at constant stagnation temperature. The output of gas turbine is the sum of actual heat drop in each row of bladings.

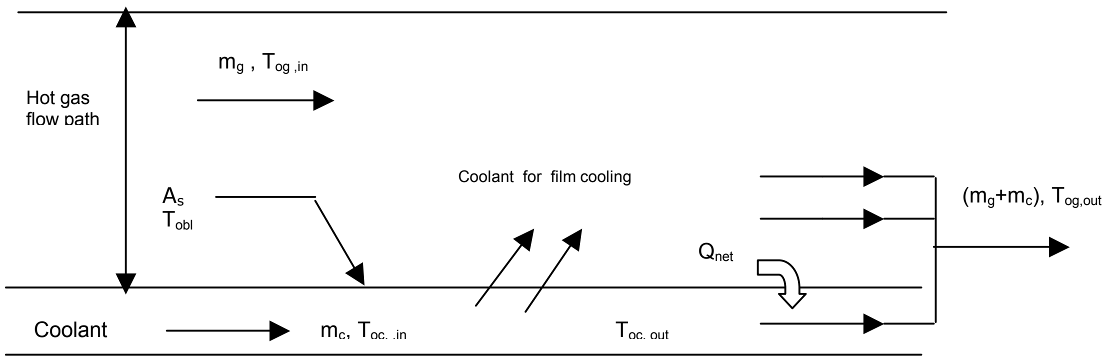

Fig. 5 (a)

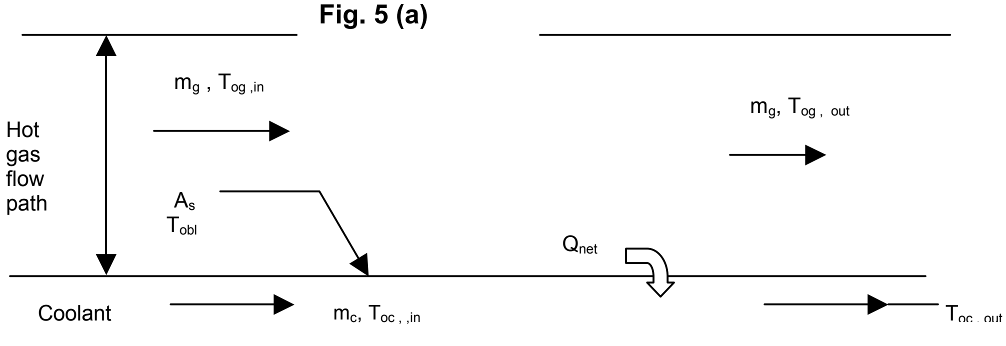

Fig. 5 (b)

Fig. 5 Simple cooling model (a) air film cooling (b) internal convection cooling- steam

METHODOLOGY AND RESULTS

Parametric study has been undertaken on plant efficiency and specific work of combined cycle for turbine inlet temperature(TIT), compressor pressure ratio(r_{pc}) gas turbine reheating pressure ratio (r_{pHPT}), reheater temperature(RIT) and turbine blade temperature(T_{bl}). The methodology for carrying out such study is to consider GT26 gas turbine burning natural gas as reference topping cycle and its independent variables are allowed to vary to obtain the optimized results. The same gas turbine that burns hydrogen-blended natural gas is subjected to steam cooling and its effects have been studied and compared with air-cooling system. The bottoming cycle parameters have been taken as fixed values which are used in common practice based on inlet temperature of exhaust gas to HRSG and limit of dryness fraction from LP turbine exhaust .

Fig. 6 and 7 show the variation of basic and reheat combined cycle efficiencies with specific work for air and steam cooling for various values of r_{pc} and TIT at r_{pHPT} =2.8. From the results it is obvious that the plant efficiency and specific work are much higher in reheat combined cycle at any r_{pc} and TIT as compared to simple combined cycle for both type of system i.e. burning one burning natural gas and other burning hydrogen-blended natural gas . For air cooled simple cycle, the optimum r_{pc} and TIT lie around 20 and 1700K respectively whereas in the case of steam cooling these values show rising trends even beyond r_{pc}=40 and TIT=1700K respectively. In the case of reheat combined cycle , these values show rising trends for both air cooling and steam cooling even beyond r_{pc}=40 and TIT=1700K.

Table 1. Input data for analysis

PARAMETER	SYMBOL	UNIT
Gas Properties:	$Cp=f(T)$ Enthalpy $h=\int cp(T)\,dT$	kJ/kg K kJ./kg
Compressor	i. Polytropic efficiency(η_{pc})=92.0 ii.Mechanical efficiency(η_{m})=98.5	% %
Combustor	i. Combustor efficiency (η_{comb})=98.5 ii.Pressure loss (p_{loss})=2.0% of entry pressure iii. Proposed Fuel = Hydrogen enriched Natural Gas (10% Hydrogen) (LHV) = 42.0 iv.Lower heating value of fuel blend (LHV) = 51.690 v. Traditional fuel NG (LHV) = 42.0	% % MJ/kg MJ/kg MJ/kg
Gas turbine	i. Polytropic efficiency (η_{pt})=93.0 ii. Exhaust pressure=1.08 iii. RIT=(TIT-100K) if TIT≥1600 =TIT if TIT≤1500 iv. Exhaust hood loss=4	% bar K K K
HRSG (Triple Pressure with reheat)	i. Effectiveness=98.0 ii. Pressure loss= 10% of entry pressure iii. Stack (minimum temperature=353.0 iv. H.P pressure = 160 v. H.P superheat= 843.0 vi. H.P steam exhaust pressure=40 vii. Reheater loss=3% of entry pressure viii. I.P pressure= 35.0 ix. I.P superheat=563.0 x. L.P pressure=6.0 xi. L.P superheat=473.0 xii. Deaerator pressure=2.0 xiii. Condenser pressure= 0.05 xiv. Gas/steam approach temperature difference= 20.0 xv. Pinch-point temperature difference= 10.0	% % K bar K bar bar bar K bar K bar bar K K
Steam turbine	i. Isentropic efficiency= 88.0 HP, 92.0 IP/LP ii. Mechanical efficiency= 98.5 iii. Minimum steam quality at LP exhaust = 0.88	% % dry
Alternator	Alternator efficiency=98.5	%

Such trends are due to the combined effect of higher r_{pc}, higher TIT, reheat, hydrogen blended fuel and cooling means. In the case of air cooling , turbine blade cooling penalties such as mixing and cooling losses are predominant and increase with TIT whereas in the case of steam cooling mixing losses are absent Such trends are due to the combined effect of higher r_{pc}, higher TIT, reheat, hydrogen blended fuel and cooling means. In the case of air cooling , turbine blade cooling penalties such as mixing and cooling losses are predominant and increase with TIT whereas in the case of steam cooling mixing losses are absent and cooling losses are also very less. Further, the full flow of gas expands in the gas turbine in the case of steam cooling.

The other important reason is the steam coolant used to cool the gas turbine gets reheated and mixed with the steam coming out from reheater of HRSG and so this amount of saved energy of HRSG generates extra steam and increases the bottoming cycle efficiency and in turn increases plant efficiency and specific work. The upward kink in the reheat cycle at and beyond TIT=1600K is due to the selection of RIT less than TIT by 100K. This saves the fuel and so upward kink in plant efficiency. The effect of hydrogen blended fuel is significant as exergy losses associated with burning of hydrogen are lower than those associated with natural gas. Also the LHV of the hydrogen-blended natural gas is higher than natural gas.

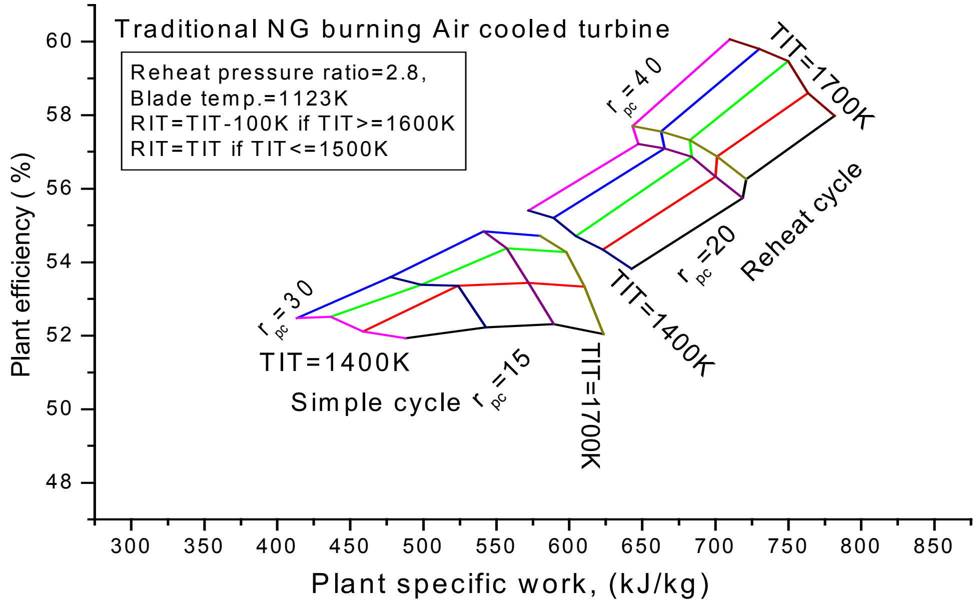

Fig. 6. Simple and reheat combined cycle plant efficiency versus plant specific work for different r_{pc} and TIT for air cooled turbine burning natural gas

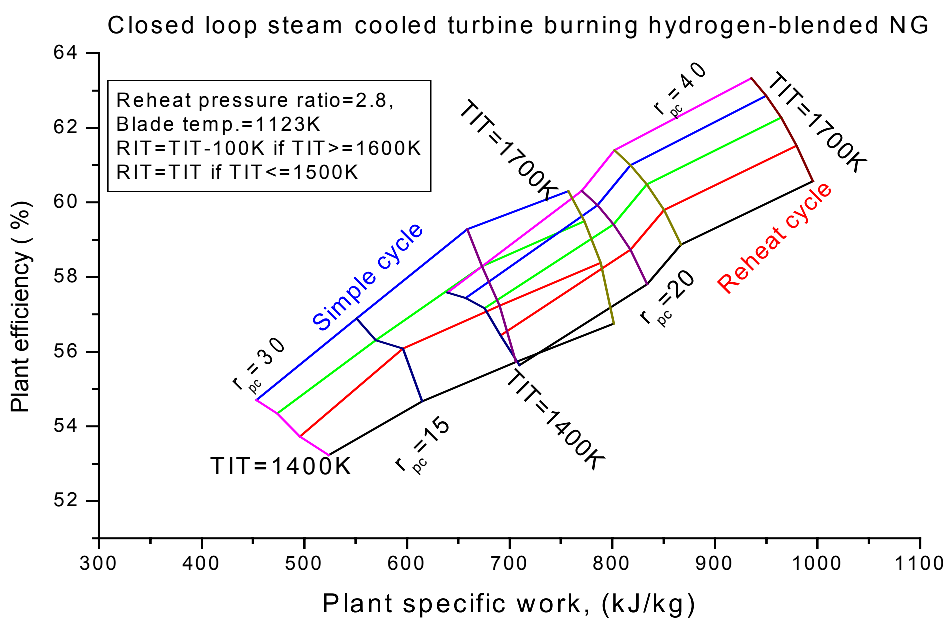

Fig. 7. Simple and reheat combined plant cycle efficiency versus plant specific work for different r_{pc} and TIT for closed loop steam cooled turbine burning hydrogen blended NG

The effect of r_{pHPT} on the plant efficiency and specific work is depicted in fig. 8. for both types of fuel types and cooling. The results show that a proper selection of r_{pHPT} is essential.

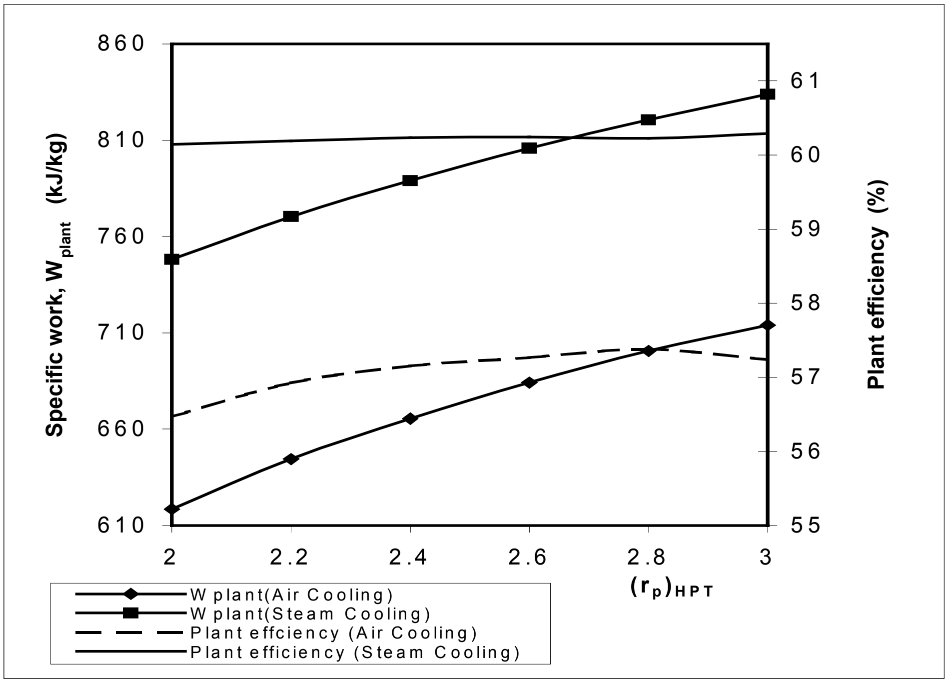

Fig. 8. Plant efficiency and Specific work versus $(r_p)_{HPT}$ for air and steam cooling

The plant specific work in both types of fuels and cooling that goes on increasing with r_{pHPT} while plant efficiency is the maximum around r_{pHPT} 2.6 to 2.8. The effect of r_{pHPT} on plant efficiency is appreciable in case of traditional fuel and air cooling whereas in the case of H_2 blended fuel and steam cooling it is not appreciable. This is due to the fact that at higher values of r_{pHPT}, the exhaust temperature of HP gas turbine is higher, so the fuel needed in reheater is less without much affecting steam cycle efficiency and compensating the cooling penalties and so in turn higher plant efficiency in the case of air cooling_while in steam cooling , the combined effect of all variables is very less. Fachini et al. [6] has reported that combined technology of GT-26 and MS9001H could lead to plant efficiency around 62 percent.

Fig. 9 shows the effect of turbine blade surface temperature (T_{bl}) on plant efficiency for air and steam cooling. For simple combined cycle it is gathered from the results that with increase in turbine blade temperature the plant efficiency increases with T_{bl} in the air cooling whereas in the steam cooling the increase in less. This is due to reduction in coolant penalties and less cooling requirement.

Table 2 depicts the summary of performance of combined cycle for simple and reheat system for both type of fuels and cooling scheme.

Conclusion:

Reheat gas/steam turbine cycle with high compressor pressure ratio yields higher efficiency and specific work over simple combined cycle. Steam cooling coupled with hydrogen blended fuel offers better performance over air cooling in terms of plant efficiency and specific work for both simple and reheat combined cycle. In reheat system r_{pHPT} plays an important role in deciding the maximum plant efficiency and specific work and its value lies around 2.8 to 3.0 for both cooling means. The selection of RIT in relation to TIT is an important consideration in achieving the maximum possible plant efficiency especially at higher TIT. Proposed hydrogen-blended natural gas burning system offers around 64 percent plant efficiency which is significant and around 25% increased plant specific work. The use of proposed hydrogen blended natural gas offers great potential.

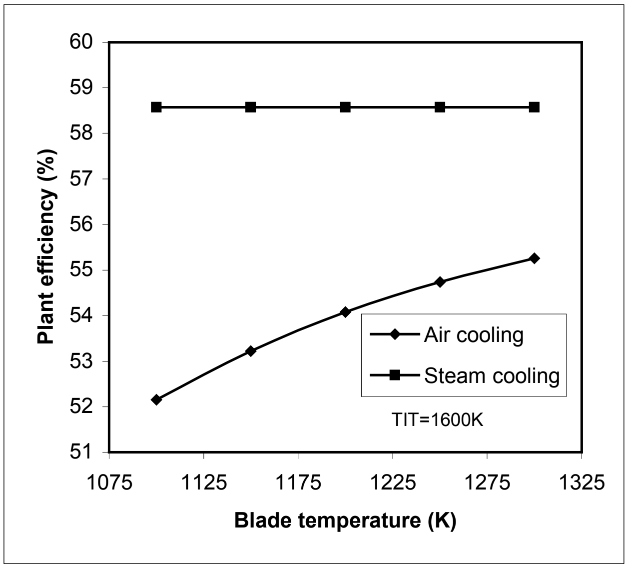

Fig. 9. Plant efficiency versus blade temperature for simple combined cycle

Table 2. A Summary of Performance of Combined Cycle

Parameter	Traditional Air Cooled turbine burning NG			Steam Cooled turbine burning hydrogen blended NG			
	Simple	Simple	Reheat	Simple	Simple	Reheat	Reheat
r_{pc}	15.0	30.0	30.0	15.0	30.0	30.0	40
TIT (K)	1700K	1700K	1700K	1700K	1700K	1700K	1700K
RIT (K)			1600K	--	--	1600K	**1600K**
$(r_p)_{HPT}$			2.8	--	--	2.8	**2.8**
η_{plant} (%)	52.0408	54.71	59.4793	56.751	60.3	62.2706	**63.32**
W_{plant} (kJ/kg)	623.426	579.938	749.95	801.58	757.32	964.5144	**935.23**

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