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THERMODYNAMIC ASSESSMENT OF IMPACT OF INLET AIR COOLING TECHNIQUES ON GAS TURBINE AND COMBINED CYCLE PERFORMANCE

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ABSTRACT

The article is focused on the comparison of impact of two different methods of inlet air cooling (vapor compression and vapor absorption cooling) integrated to a cooled gas turbine based combined cycle plant. Air film cooling has been adopted as the cooling technique for gas turbine blades. A parametric study of the effect of compressor pressure ratio, compressor inlet temperature (T i,C), turbine inlet temperature (T i, T), ambient relative humidity and ambient temperature on performance parameters of plant has been carried out. Optimum T i,T corresponding to maximum plant efficiency of combined cycle increases by 100o C due to the integration of inlet air cooling. It has been observed that vapor compression cooling improves the efficiency of gas turbine cycle by 4.88 % and work output by 14.77 %. In case of vapor absorption cooling an improvement of 17.2 % in gas cycle work output and 9.47 % in gas cycle efficiency has been observed. For combined cycle configuration however vapor compression cooling should be preferred over absorption cooling in terms of higher plant performance. The optimum value of compressor inlet temperature has been observed to be 20oC for the chosen set of conditions for both the inlet air cooling schemes.

INTRODUCTION

The drive to achieve higher efficiency and lower emissions has led to the advancement of thermal power plants based on complex gas turbine cycles. Rapid growth in electricity demand especially during summer months, results in the need to build power plants that generate maximum output at summer ambient temperature ratings. A disadvantage, that penalizes the gas turbine peaking plant rating, is the inversely proportional effect of the ambient temperature on the gas turbine output.The adverse effect of high ambient air temperatures on the power output of a gas turbine is two-fold: as the temperature of the air increases, the air density and, consequently, the air mass flow decreases. The reduced air mass flow directly causes the gas turbine to produce less power output. On the other hand, the higher intake-air temperature results in an increase of the specific compressor work and, therefore, in a further reduction of the power output. Other effects of the higher intake air temperature are the increase of the heat rate (HR) and decrease of the compression ratio, as well as the increase of the gas turbine exhaust temperature and decrease of the exhaust gases mass flow. A gas turbine loses approximately 7 % of its nominal power when the intake temperature increases from 15 ^{o}C (ISO conditions) to 25 ^{o}C. The losses are still bigger, reaching even 15 % of the power rating at 36 ^{o}C ambient temperature. In such conditions, power augmentation should be essentially carried out. Also a little enhancement in thermal efficiency could result in a better exploitation of fuel and hence reduced emission. A simplest way to counter such challenges is cooling the air at inlet to compressor.

Inlet air cooling of gas turbine and combined cycle power plant has been a subject of investigations in the past. An extensive review of various inlet air cooling technologies along with their benefits and drawbacks have been done by Ibrahim and Varnham [2]. In case of vapor compression refrigeration system as the working cycle closely follows the Carnot cycle, the C.O.P is high. The vapor compression refrigeration system is also somewhat simpler and less costly than other competing cooling systems, but there may be risk of refrigerant leakage into gas turbine.

LITERATURE REVIEW

Alhazmy and Najjar have analysed the inlet air chilling using a cooling coil and observed that the cooling coil improves the turbine output by 10 % during cold humid conditions and by 18 % during hot humid conditions. However, net power generated from the plant drops by 6.1 % during cold and humid conditions and 37.6 % during hot and humid conditions.

Amell and Cadavid [4] have examined the influence of the relative humidity on the atmospheric air-cooling thermal load of gas powered thermal station (GPTS) installed in Colombia. The inlet air cooling techniques investigated were vapor compression and ice storage based systems.

Srivastava and Yadav [5] have investigated the performance of a combined cycle using vapor compression refrigeration system. The result shows that the plant specific work of the combined cycle increases by 4 % and plant efficiency by 0.39 percentage point when the inlet air is cooled by 20K from 300 K to 280 K.

Lucia et al. [6] have examined the operation of cogeneration gas turbine power plant with and without an air cooling system and concluded that in the Italian climate, the turbine power output may increase by upto 19 %, if the compressor inlet air is cooled to 10 °C.

Alhazmy et al. [7] have reported that the mechanical refrigeration improves the gas cycle specific power by upto 11 % while the efficiency is reduced by 2.25 %.

Al-Ansari and Ali [8] have analyzed a hybrid turbine inlet air cooling (TIAC) system consisting of mechanical chilling followed by evaporative cooling applied to a gas turbine power plant in Saudi Arabia. An enhancement of more than 10 % power has been reported. The cost operation analysis shows clearly that the hybrid TIAC method with wet cooling has the advantage over the other analyzed methods and it would be profitable to install it in the new gas turbine power plants.

Sanaye et al. [9] have performed a thermo-economic analysis of ice thermal energy storage system for gas turbine inlet cooling application. The system comprises of a gas turbine, air cooler, and a thermal energy storage unit with vapor compression refrigeration cycle. The addition of inlet air cooling has been reported to enhance power by 3.9- 25.7 % and efficiency by 2.1-5.2 % while the pay back period was increased by 3.7 years. Another promising inlet air cooling method is vapor absorption cooling, as it uses a low grade thermal energy source to drive the system and generate the cooling effect. Most common absorption cooling systems are the LiBr–H–2O and NH3 H2O systems.

Najjar [10] has analyzed an aqua-ammonia absorption chiller and reported improvement in simple cycle efficiency and power by cooling the inlet air using an absorption system.

Mohanty and Paloso [11] have used a lithium-bromide, double-effect absorption chiller which produced as much as 11 % additional electricity from the same gas turbine power plant.

A study by Kakaras et al. [12] revealed that the absorption chiller can considerably increase the power output, although there is a reduction in thermal efficiency.

Boonnasa et al. [13] have summarized that the addition of absorption chiller could increase the power output of a gas turbine (GT) by about 10.6 % and the combined cycle power plant by around 6.24 % annually.

It was reported that the addition of an absorption inlet air cooling, could increase the optimum efficiency of gas turbine cycle by 7.48 % and specific work by more than 18 %.

Despite numerous research on inlet air cooling the literature review reveals the following.

- All the studies made so far represent the effect of vapor compression inlet air cooling on gas turbines without considering the effect of blade coolant mass on its performance.
- None of the previous literature has reported the effect of vapor compression inlet air cooling on dual pressure HRSG based combined cycle.
- The study of the effect of ambient temperature, ambient relative humidity, compressor pressure ratio, compressor inlet temperature and turbine inlet temperature on the performance of vapor compression inlet cooling systems integrated to cooled gas turbine based combined cycle plant has not been investigated in literature.
- The comparative analysis of inlet cooling methods integrated to cooled gas turbine based combined cycle has not been discussed in literature.

The present article bridges the research gap by performing a comparative analysis of impact of vapor compression and vapor absorption inlet air cooling applied to dual pressure HRSG based combined cycle with film air cooling of gas turbine blades. The prime objective of the present study is to highlight the benefits of incorporating inlet air cooling system to a cooled gas turbine based combined cycle plant. This allows a higher T i,T to be adopted in comparison to a non-inlet cooled cycle and thereby ensures higher plant performance. In this article, the effects of compressor pressure ratio, compressor inlet temperature, turbine inlet temperature, ambient relative humidity and ambient temperature have been investigated on the thermodynamic performance of the cycle.

COMPONENT MODELING AND GOVERNING EQUATIONS

Parametric study of the inlet air cooled combined cycle using two different means of inlet air cooling has been carried out by modeling the various elements of a combined cycle and using the governing equations. Following sub-sections detail the modeling of various elements of the cycle.

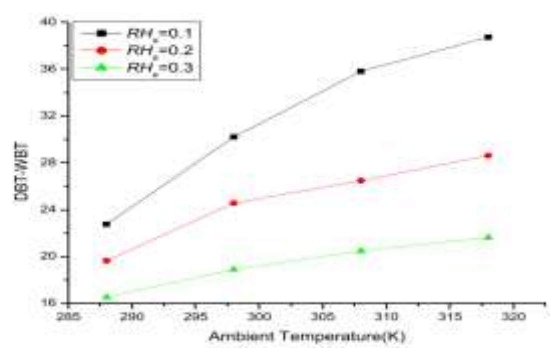
Vapor compression inlet air cooling system

A vapor compression refrigeration cycle has been used to cool the compressor inlet air. The work of refrigeration needed for cooling the inlet air has been extracted from the gas turbine output. In case of vapor compression refrigeration system, as the working cycle has been assumed to closely follow the Carnot cycle, the COP has been assumed to be high. The vapor compression system is somewhat simpler and less costly than vapor absorption cooling system, but there may be risk of refrigerant leakage into gas turbine.
Special alarm systems have to be installed to detect refrigerant leakage into the compressor and to shut down and evacuate the refrigerant. The refrigeration work of vapour compression refrigeration has been calculated by using the following relation.

$$-W_{\text{ref}} = \frac{Q_{\text{CL}}}{\text{COP}_{\text{VC}}(1-\mu x)^n \eta_{\text{eu}}}$$

Where m is an empirical constant that depends on the type of refrigerant and x is the quality of the refrigerant at the exit of IAC system. A low global warming potential (GWP) refrigerant having zero ozone depletion potential (ODP), R32 has been selected which has the potential of economically satisfying the requirements for safety and environmental protection. The empirical constant 'n' depends on the number of compression and expansion stages and in this article the value of n ¼ 1 for a simple refrigeration cycle having single stage compressor.
The theoretical COP of the cycle at different condenser and evaporator temperatures has been calculated from the properties (enthalpy) of refrigerant and the actual COP is calculated by introducing a term refrigeration efficiency (h_{Ref}) defined as

$$\eta_{\text{Ref}} = \frac{\text{COP}_{\text{actual}}}{\text{COP}_{\text{theoretical}}}$$



Effect of ambient temperature and ambient RH on the difference between DBT and WBT

Vapor absorption inlet air cooling system

In this method of cooling, inlet air to the compressor is cooled from ambient temperature to a lower temperature by means of an 'ammonia-water' vapor absorption refrigeration system. Of the following three options of thermal energy source to drive the system, option-3 has been found suitable, for the reason discussed as under:

Option-1: exhaust gases at the exit of HRSG, has the limitation of its temperature close to the dew point temperature and further extraction of heat from it would lead to condensation of moisture in the flue gases having SOx/NOx. This results in weak acid formation on the heat exchanger tubes of absorption chiller and resulting its corrosion.

Option-2: utilizing steam extracted from IP/LP steam turbine casing having energy just sufficient to meet the absorption chiller energy requirement. This is not appropriate as it results in greater loss of steam cycle work due to bleeding of steam that would otherwise have been used to generate steam cycle work.

Option-3: exhaust gas extracted at an appropriate point prior to the exit of HRSG having sufficient heat energy, has been found to be most suitable for utilization in absorption chiller. The heat from HRSG is extracted at an exhaust gas temperature of 120 C which is the ideal generator temperature in an aqua ammonia vapor absorption system.

To model the vapor absorption system the following assumptions have been made.

- The temperature of gas leaving the vapor absorption (VA) generator is restricted to a minimum level of 373 K to safeguard against the possible moisture condensation present inside the gas.
- The concept of heat transfer effectiveness of VA generator (εgen) has been introduced to account for the actual heat input in the VA generator.
- The pump work of the absorption system is negligible.

The amount of heat required to run the absorption refrigeration system for the selected COP has been determined by:

$$Q_{abs} = Q_{CL}/(COP)_{VA}$$

Hence, the heating load of the VA generator, taking into account its effectiveness, is determined by:

$$Q_{gen} = Q_{abs}/\varepsilon_{gen}$$

$$\dot{m}_{w,i} = \dot{m}_{w,e}$$

$$w_p = \Sigma v_{w,i}(p_e - p_i)$$

3. Performance Parameters:

The general expressions to calculate the performance parameters for gas turbine and combined cycle plant are given as follows:
The gas cycle power (W_{gc}) is given by,

$$\dot{W}_{gc,net} = \dot{W}_{gt} - \frac{|\dot{W}_c + \dot{W}_{ref}|}{\eta_m}$$

W ref = 0, in case of VA based inlet air cooling system.
The gas turbine (topping cycle) efficiency (η_{gt}) is expressed as:

$$\eta_{gt} = \frac{\dot{W}_{gc,net}}{\dot{Q}_A} = \frac{\dot{W}_{gc,net}}{\dot{m}_f \cdot \Delta H_r}$$

The steam cycle power (W sc) is given by:

$$\dot{W}_{sc,net} = \dot{W}_{st}.\eta_m - \frac{|\dot{W}_p|}{\eta_p}$$

Where 'n$_p$' is the overall pump efficiency and 'n$_{st}$' is pump power

The steam turbine (bottoming) cycle efficiency (n$_{st}$) is expressed as:

$$\eta_{st} = \frac{\dot{W}_{st,net}}{\dot{Q}_{hrsg,i} - \dot{Q}_{gen,i}}$$

where Q_{hrsgj} = heat entering to HRSG = $m_{ghrsg,I,}$ $h_{g,hrsgi}$ and heat supplied to VA generator =$Q_{gen,i}$.$h_{g,gen,I}$ which would be zero in case of VC based inlet air cooling system.

The combined cycle plant power (*Wplant*) is given by:

W $_{Plant}$ = n $_{alt}$ [W $_{gc,net}$ = W s$_{c,net}$]

The combined cycle plant efficiency (η $_{plant}$) is expressed as:

$$\eta_{plant} = \frac{\dot{W}_{plant}}{\dot{m}_f \cdot \Delta H_r}$$

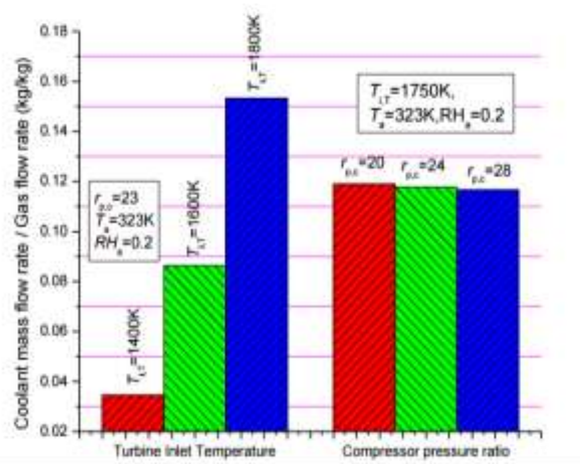
Modeling of cycle components and governing equations developed for cycles proposed above have been coded using C++ and results obtained. A flowchart of the programme code 'Comb-IAC' illustrating the method of solution is detailed in the author's earlier article.

RESULTS AND DISCUSSION

The influence of inlet air cooling on combined cycle plant performance has been shown through the performance curves, plotted using modeling, governing equations and input parameters (Table1). In the present work the effect of vapor compression and absorption inlet air cooling have been studied for 2PR combined cycle plant configuration by varying various parameters and the results obtained have been analyzed as under:

Effect of turbine inlet temperature and compressor pressure ratio on requirement of coolant flow.

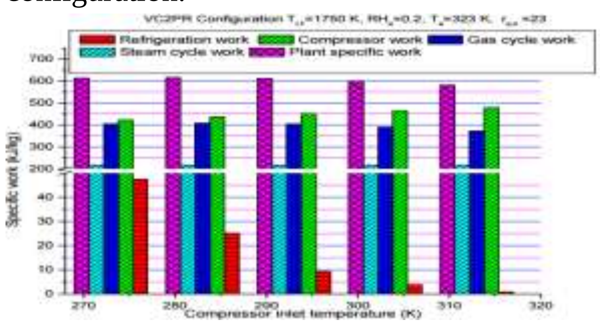
Fig. shows the requirements of blade coolant flow rates with variation in turbine inlet temperature and compressor pressure ratio. It can be seen that the coolant flow rate increases significantly with increase in *T* i,T in order to maintain the turbine blade temperature within specified limits. However, the variation in cooling flow rates with change in compressor pressure ratio is not appreciable rather monotonous. This is because of the fact that increase in compressor pressure ratio has no significant affect on the bled air coolant temperature.



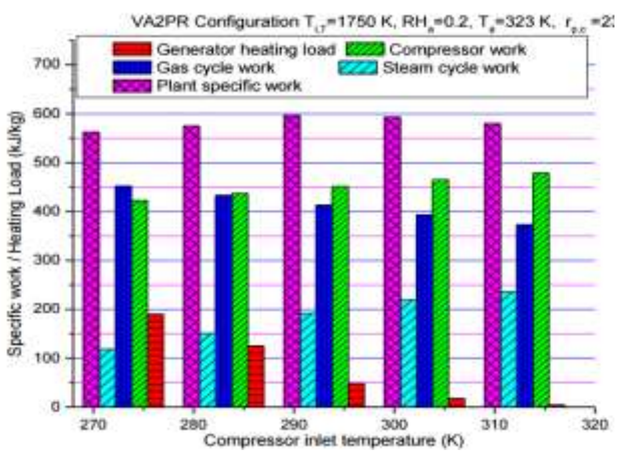
Coolant flow requirement with variation in turbine inlet temperature and compressor pressure ratio

Sensitivity of various components of plant work output with T i,C for IAC2PR Configurations.

Fig. (a) shows the effect of variation of *T* i,C on various components of work output for VC2PR configuration. It is observed that as the *T* i,C decreases, the compressor work decreases, while there is an increase in the work of refrigeration. The combined effect is such that the gas cycle work increases. Since the steam cycle work is independent of the variation in *T* i,C , the net result is an increase in plant work output with a decrease in *T* i,C . Fig. (b) shows the effect of *T* i,C on components of work output and VA generator load and for VA2PR configuration.



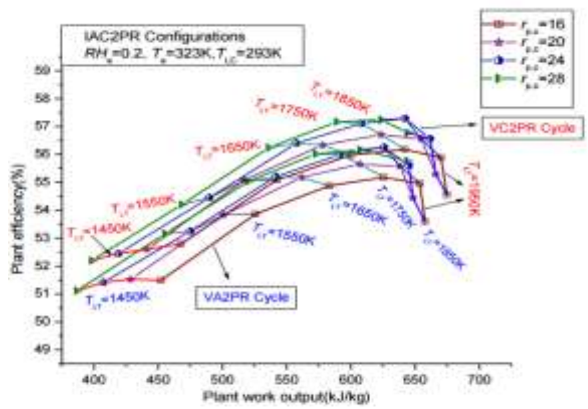
Variation of plant and component specific works with $T_{i,C}$ for VC2PR configuration



Variation of various specific works and VA generator load with $T_{i,C}$ for VA2PR configuration

As discussed above with decrease in *T* i,C , the compressor work decreases, while the cooling load increases. The result is an increase in gas cycle work. Since the heat required to run the IAC system is extracted from exhaust gas prior to the exit of HRSG, the mass flow rate of steam generation reduces, resulting in corresponding decrease in steam cycle work. The combined effect is such that the plant work output is affected as discussed for Fig.(a).

Performance map of plant efficiency and plant work output of IAC2PR configurations for variation in rp,c and T i,T .



Effect of $r_{p,c}$ and $T_{i,T}$ on plant efficiency and plant work output for VC2PR & VA2PR cycle

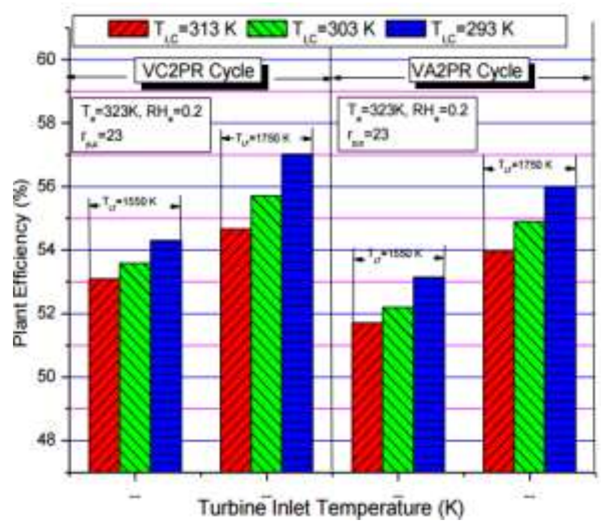
Fig. Shows the effect of *r* p,c and *T* i,T on plant work output and plant efficiency for IAC2PR configurations. It is observed from the results that at any *r* p,c, the plant efficiency increases with *T* i,T to a certain value and thereafter starts decreasing. The plant work output is observed to increase rapidly upto an optimum value of *T* i,T , whereafter this increase is slower. It has also been observed that at any *T* i,T , the plant efficiency first increases and then decreases with increase in *r* p,c. There exists an optimum *r* p,c at any *T* i,T with reference to plant efficiency.

Comparing the two methods of inlet air

cooling, it is observed that the performance map of VC2PR is positioned a little above and to the right to that of VA2PR map indicating that the integration of VC inlet air cooling is more beneficial compared to VA cooling for the proposed configuration in terms of higher plant output and higher plant efficiency for selected range of *r* p,c and *T* i,T . The relative gain in performance is higher at higher *T* i,T and lower *r* p,c.

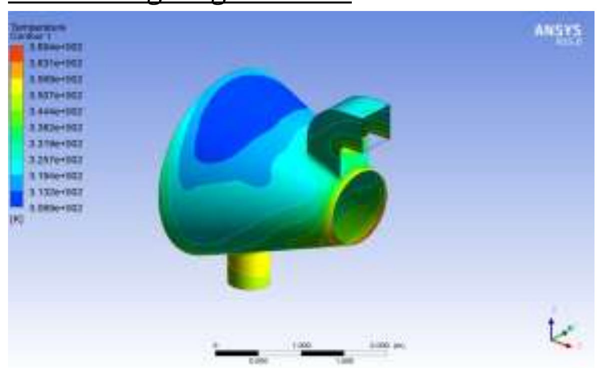
Effect of T i,C on plant efficiency and plant work output of IAC2PR cycles for variation in T i,T .

Fig. (a) and (b) represents the effect of *T* i,C on plant efficiency and plant work output of IAC2PR cycles for different values of *T* i,T. It is observed that the plant efficiency and plant work output increases with increase in *T* i,T and decrease in *T* i,C as explained in earlier sections. The effect of reduction in *T* i,C on plant performance is more pronounced at higher *T* i,T. This is because at very high value of *T* i,T, there is a greater blade coolant requirement, and at lower value of *T* i,C, the low temperature blade coolant is more effective as a coolant. As the *T* i,C is reduced, there is a corresponding reduction in blade coolant requirement, which in turn results in lower pumping and mixing losses. The effect of these parameters increases the plant performance more effectively.

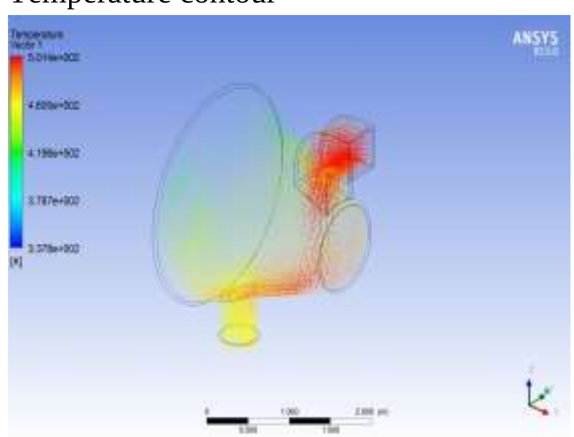


Effect of T $_{i,C}$ and T $_{i,T}$ on plant efficiency of inlet air cooled configurations

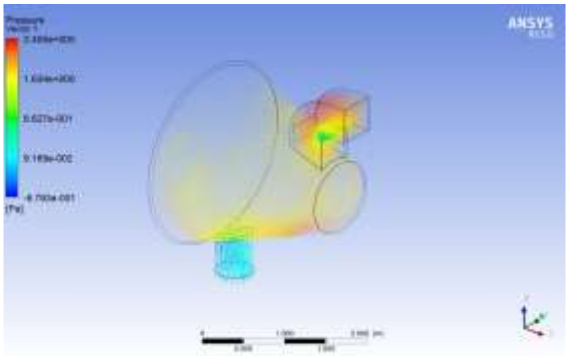
Thermodynamic Analysis of Impact of Inlet Air Cooling on gas turbine



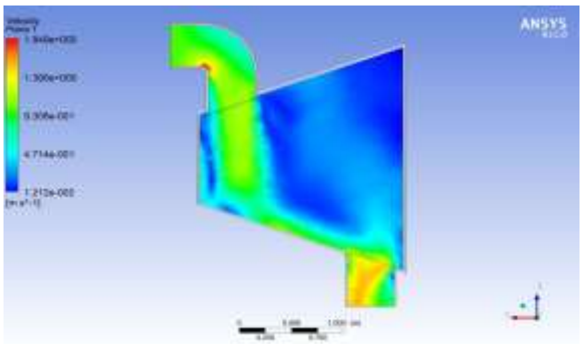
Temperature contour



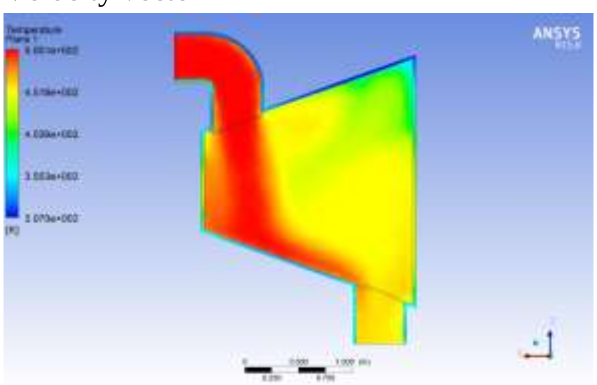
Temperature vector



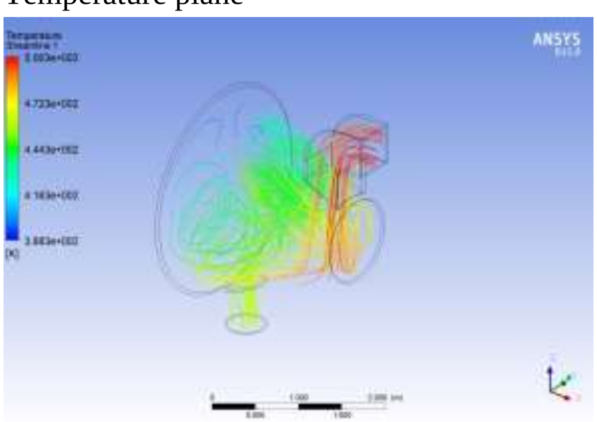
Pressure vector



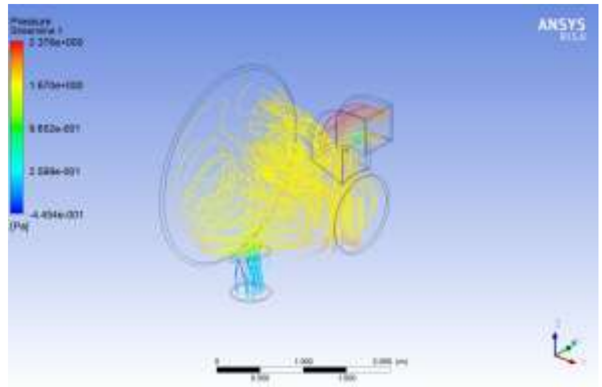
Velocity vector



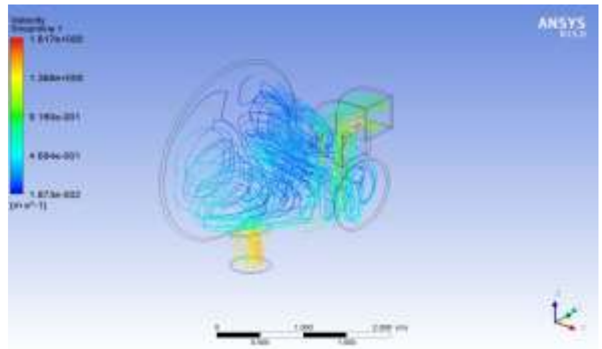
Temperature plane



Temperature stream line



Pressure streamline



Velocity sreamline

CONCLUSIONS

Based on the analysis of integration of vapor absorption and vapor compression inlet air cooling to gas turbine and combined cycle plants, the following conclusions have been drawn:

1. The best ambient conditions to incorporate inlet air cooling are high ambient temperature and low ambient relative humidity which yield better performance of gas turbine and combined cycle than that without inlet air cooling

2. Inlet air cooling enables to increase the turbine inlet temperature even by upto 100^{o}C yielding high efficiency without the need to go for improved blade material.

3. It is observed that as the T i,C is reduced, the blade coolant mass flow rate decreases. The effect of reduction in T i,C on

performance parameters therefore has a more significant effect at higher values of $T_{i,T}$.

4. The integration of vapor compression cooling improves the plant efficiency of BGT by 4.88 % and plant work output by 14.77 %.

5. For 2PR combined cycle configuration, the vapor compression inlet air cooling improves the plant specific power by 9.02 % compared to 6.09 % for absorption cooling.

6. The optimum value of compressor inlet temperature corresponding to maximum plant performance has been found to be at 293 K for both VC2PR and VA2PR cycles.

7. A combination of optimum $r_{p,c}$ and $T_{i,T}$ is observed to be as: $T_{i,T}$ =1500K, $r_{p,c}$ =20 & $T_{i,T}$ =1800K , $r_{p,c}$ =28

REFERENCES

1. Chakartegui R, Espadafor F J, Sanchez D, Sanchez T. Analysis of combustion turbine inlet air cooling systems applied to an operating cogeneration power plant. Energy Conversion and Management 2008; 49: 2130–141.

2. Ibrahim AM, Varnham A. A review of inlet air-cooling technologies for enhancing the performance of combustion turbines in Saudi Arabia. Applied Thermal Engineering 2010; 30:1879-88.

3. Alhazmy MM, Najjar YSH. Augmentation of gas turbine performance using air coolers. Applied Thermal Engineering 2004; 24: 415–29.

4. Amell AA, Cadavid FJ. Influence of the relative humidity on the air cooling thermal load in gas turbine power plant. Applied Thermal Engineering 2002; 22: 1529–33

5. Srivastava G, Yadav R. Effect of inlet air refrigeration on the performance of combined cycle power plants. ASME Conference Proceedings 2004; Paper No POWER 2004-52147: 353-60

6. Lucia M, Bronconi R, Carnevale E. Performance and economic enhancement of cogeneration gas turbines through compressor inlet air cooling. Transactions of ASME, Journal of Engineering for Gas Turbines and Power 1994;116: 360-65

7. Alhazmy MM, Jassim RK, Zaki GM. Performance enhancement of gas turbines by inlet air cooling in hot and humid climates. International Journal of Energy Research 2006;30: 777-97

8. Al-Ansari, HA, Ali MA. Impact of the use of a hybrid turbine inlet air cooling system in arid climates. Energy Conversion and Management 2013;75:214-23

9. Sepehr S., Fardad A., Masoud M.,Thermoeconomic optimization of an ice thermal storage system for gas turbine inlet cooling. Energy 36(2);2011:1057-67

10. Najjar Yousef SH. Enhancement of Performance of Gas Turbine Engines by Inlet Air Cooling and Cogeneration System. Applied Thermal Engineering 1996; 162: 163-73

11. Mohanty B, Paloso Jr G. Enhancing gas turbine performance by intake air cooling using an absorption chiller. Heat Recovery Systems & CHP 1995; 15: 41-50

12. Kakaras E, Doukelis A, Karellas S. Compressor intake-air cooling in gas turbine plants. Energy 2004;29:2347–58.

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