



## THERMODYNAMIC MODELLING AND ANALYSIS OF COOLING CHAMBER WITH VAPOUR COMPRESSION AND VAPOUR ABSORPTION COOLING-FEASIBILITY STUDY

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### Abstract

*The project work is around the correlation of effect of two unique strategies for air cooling incorporated to a cooled gas turbine based joined cycle plant. Air film cooling has been received as the cooling procedure 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  $100^\circ$  C due to the integration of inlet air cooling. Vapour compression cooling should be preferred over absorption cooling in terms of higher plant performance. The ambient conditions of temperature and pressure are  $25^\circ$ C and 1.013 bar.*

**Keywords:** *Inlet air cooling techniques, cycle performances, impact on gas turbine.*

### 1.0 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 oC (ISO conditions) to 25 oC. The losses are still bigger, reaching even 15 % of the power rating at 36 oC 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.

### Modelling of inlet air cooling systems:

The path that air takes on the psychometric chart as it undergoes change from ambient state (a) to the desired cooled state (c). By rejecting its sensible heat, the air temperature drops, while the relative humidity continues to rise until its dew point is reached (point 'b'). Any further cooling from this point will require removal of a much greater quantity of heat due to the removal of latent heat of condensation of the water vapor along with the sensible heat, which the air contains. This process continues until it reaches the desired temperature at point 'c'. The air cooling process has been plotted in Fig. with heavy lines a-b-c. The sensible cooling loads are shown as dec and latent cooling loads are shown a-d. The total cooling load comprises of the heat required to reduce the temperature from its initial ambient condition to the desired cooled state, i.e. the sensible heat of air and the heat required to condense the moisture contained in the air (the latent heat). So the total inlet air cooling load or the refrigerating effect can be computed as under:

### Vapour compression inlet air cooling system

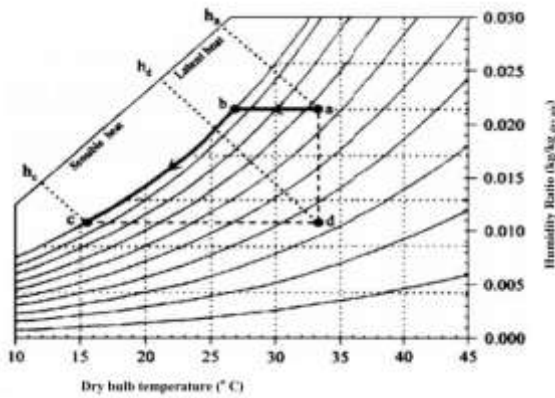
A vapour compression refrigeration cycle has been used to cool the compressor inlet air. The work of refrigeration needed for cooling the inlet air has been extracted from the gas turbine output. In case of vapour compression refrigeration system, as the working cycle has been assumed to closely follow the Carnot cycle, the COP has been assumed to be high. The vapour compression system is somewhat simpler and less costly than vapour 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.

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

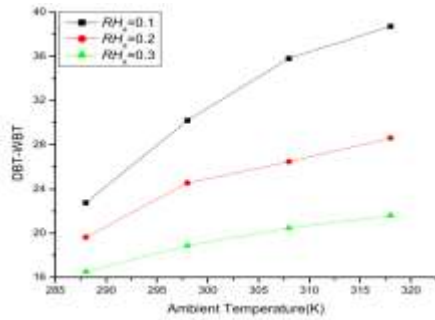
where m is an empirical constant that depends on the type of refrigerant and x is the quality of the refrigerant at the exit of IAC system. A low global warming potential (GWP) refrigerant having zero ozone depletion potential (ODP), R32 has been selected which has the potential of economically satisfying 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  $\frac{1}{4}$  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 ( $\eta_{Ref}$ ) defined as

$$\eta_{Ref} = \frac{COP_{actual}}{COP_{theoretical}}$$



**Fig** Representation of air cooling process on psychrometric chart



**Graph 1** 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 SO<sub>x</sub>/NO<sub>x</sub>. 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 chilled. The heat from HRSG is extracted at an exhaust gas temperature of 120 C which is the ideal generator temperature in an aqua ammonia vapour absorption system.

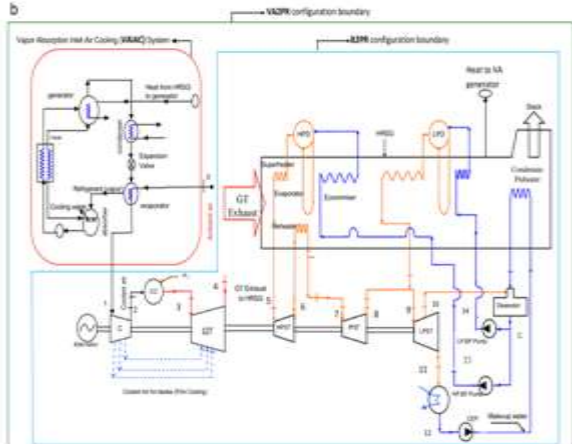


Figure 1(a) and 1(b) shows the schematic diagram of a dual pressure HRSG combined cycle with vapour compression / vapor absorption system.

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 has been introduced to account for the actual heat input in the VA generator.
- The pump work of the absorption system is negligible.

## 2.0 literature review:

[1] NaeimFarouk<sup>1</sup> , Liu Sheng<sup>2</sup> , Qaisar Hayat<sup>3</sup> (2013) Efficiency and electric-power output of gas turbines vary according to the ambient conditions. The amount of these variations greatly affects electricity production, fuel consumption and plant

incomes. The purpose of the present study is to investigate the effect of the ambient temperature on the performance of gas turbines. We observed that the power decreases due to reduction in air mass flow rate

[2] RanuRajoria<sup>1</sup> ,Arif khan (2016)” study of a gas turbine power plant incorporated with an evaporative inlet air cooler..Performance curves shows that the pump work for the evaporative inlet cooler is in accordance with the mass flow rate of water, Performance curves shows that the specific output of the cycles slightly increases at evaporative inlet cooling.

Amir Abbas Zadpoor, Ali HamedaniGolshan,(2006) have done a combined energy and energy analysis of a combined heat and power plant with absorption inlet cooling and evaporative aftercooling and reported that the most significant energy destruction rates in the cycle are in combustion chamber, heat recovery steam generator and regenerative heat exchanger. The energy efficiency, energy efficiency and power to heat ratio of the cycle are significantly influenced by the overall pressure ratio and turbine inlet temperature and slightly by the process steam parameters.

F. Haglind,(2008) 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 vapour 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 vapour absorption cooling, as it uses a low grade thermal energy source to drive the system and generate the cooling effect

### 3.0 METHODOLOGY:

This study deals with the thermodynamic analysis of gas turbine cycle with an evaporative inlet air cooling. The present parametric study of the gas turbine cycle has been carried out by modeling its various elements and deriving governing equations. In this chapter the modeling of various elements of the gas turbine cycle is considered.

#### Gas turbine cycle modelling:

A Brayton cycle with four different configurations has been considered for this present analysis.(12) An evaporative inlet air cooler is incorporated with the compressor for each configuration to cool the air at the inlet of the compressor and a difference of 10°C between the ambient temperature and the temperature at the compressor inlet, i.e. in each case it is considered that the inlet evaporative cooler cools the ambient air to 10°C.

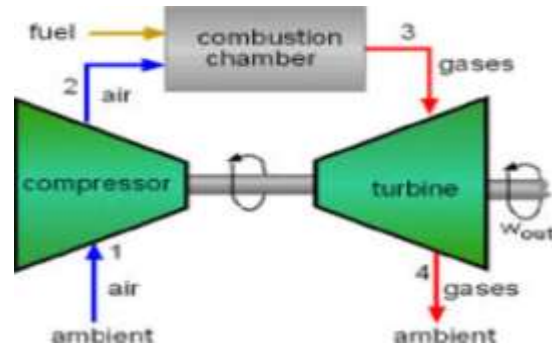


Figure Gas turbine cycle modelling

Real gas effect is considered i.e. specific heat of gas vary with respect to the temperature and specific gas constant  $R = 0.287 \text{ kJ/kg-K}$ . The gas turbines cycles taken here are open type ideal cycles and all the processes in the cycle are steady flow. Compression and expansion processes are adiabatic and changes in K.E and P.E. are negligible. Fuel taken was natural gas with  $42 \times 10^3 \text{ kJ/kg-K}$  as calorific value. The ambient pressure was taken as 1 bar = 105 Pa. Heat capacity ratio of ambient air ( $\gamma$ ) is taken as 1.4. The pressure ratio is taken as 10 and for staging in the compressor, stage pressure ratio ( $\sigma$ ) has been taken as 1.2. Pressure loss is considered in the combustion chamber and in the ducts comprising a total of 4%.

#### Combustion chamber modelling:

The combustor burns large quantity of fuel in the presence of compressed air provided by the compressor. It produces in turn hot gases which then is supplied to gas turbine. Chemical energy is converted into heat energy in the combustor, which is later Combustion chamber or simply combustor in a gas turbine is the part where fuel is converted into work by the turbine. The

process involves breaking down of heavy hydrocarbon molecules into lighter fraction molecules. Generally air-fuel ratio of open type gas turbines varies from 50:1 to 200:1 to get efficient combustion and keep the turbine inlet temperature down to permissible limit. Combustors are carefully designed first to mix and ignite the air and fuel and then mix in more air to complete the combustion process. Now a days three main configurations of the combustor exists: can, annular and can-annular. Natural gas (methane) is used in the combustion chamber as the fuel which results in less carbon emission. It is burnt in the presence of compressed air from the compressor and hereafter the working fluid of the cycle changes from air to gas.

#### Gas modelling:

The composition of air by mass is considered as 77.44% N<sub>2</sub> + 20.76% O<sub>2</sub> + 0.92% Ar + 0.85% H<sub>2</sub>O + 0.03% CO<sub>2</sub> The specific heat of air varies with temperature and also with pressure in actual conditions, if the pressure is very high. In the present configuration however, it is assume that specific heat of air varies with temperature only. The specific heat of air at constant pressure has been adopted from The temperature ranges for the specific heat of air is considered is: For the temperature range of 250 to 599K and valid up to 100 bar,

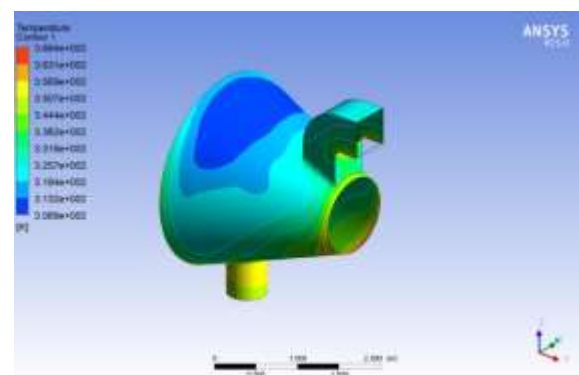
$CP,a= 1.023201 - 1.76021 \times 10^{-4} T + 4.0205 \times 10^{-7} T^2 - 4.87272 \times 10^{-11} T^3$  For the temperature range of 600 to 1500 K and valid up to 100 bar,

$CP,a = 0.874334 - 3.22814 \times 10^{-4} T + 3.58694 \times 10^{-8} T^2 - 1.99196 \times 10^{-11} T^3$  In the combustion chamber fuel is burnt in the presence of air and hot gases are produced. In this study the specific heat of gas varies with the variation in the temperature.

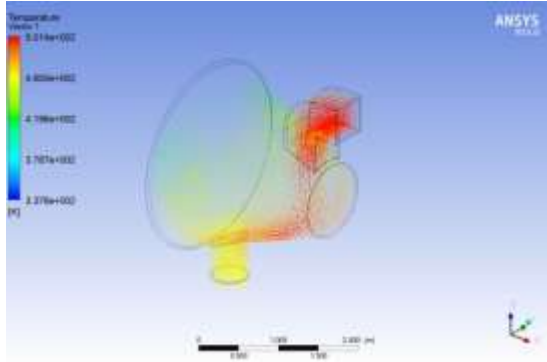
#### Inlet evaporative cooler modelling:

The present analysis deals with the evaporative type inlet air cooler. (1)Using sprays to sprinkle fine mist of water through which air is passed, as a result air drops temperature to wet bulb temperature. Both the factors, ambient temperature and relative humidity dictates the temperature of the air coming out of the cooler. Thus the evaporative inlet air cooler works as an adiabatic saturator that delivers air to the compressor with 100% relative humidity at lowered temperatures.

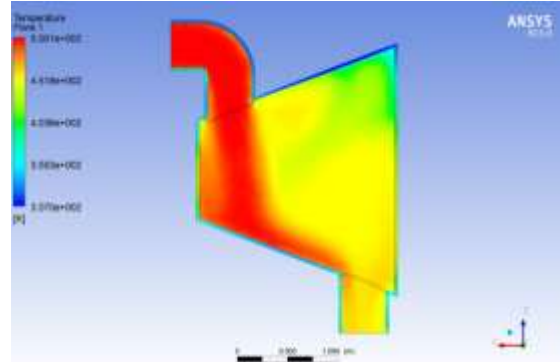
#### 4.0 Thermodynamic Analysis of Impact of Inlet Air Cooling on gas turbine



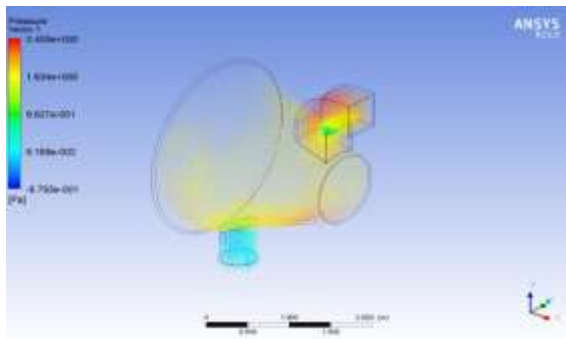
Temperature contour



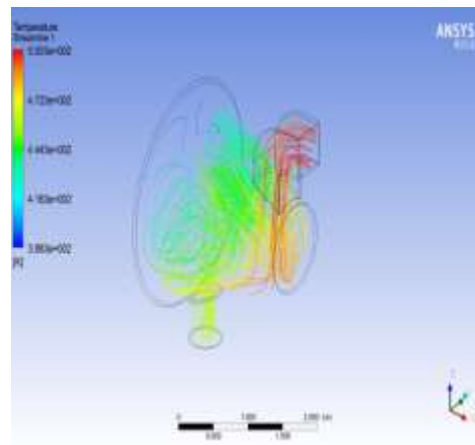
Temperature vector



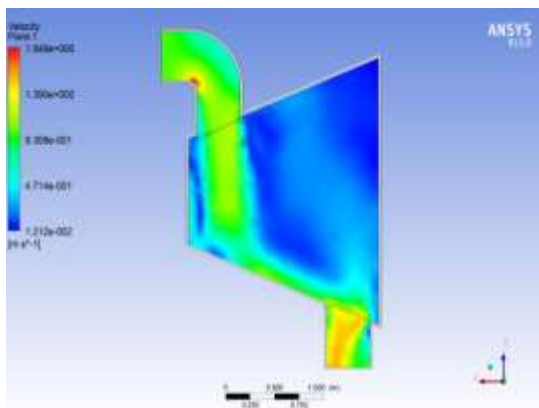
Temperature plane



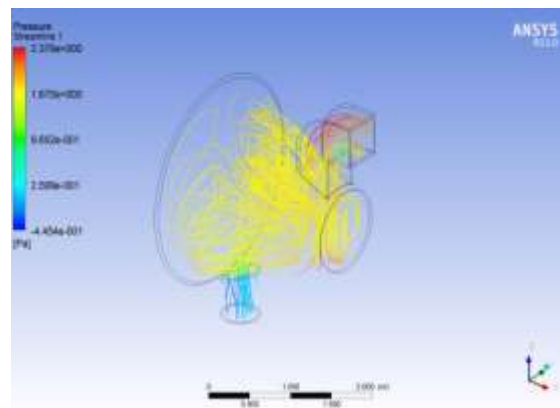
Pressure vector



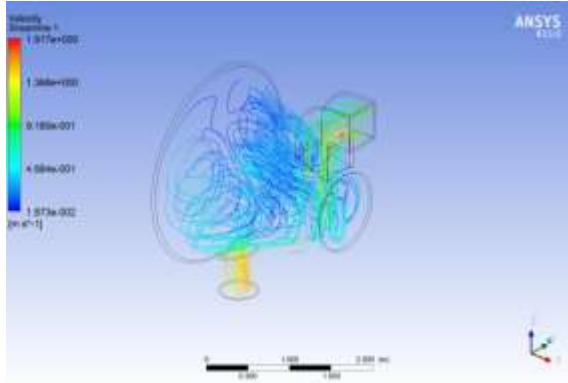
Temperature stream line



Velocity vector



Pressure streamline



Velocity streamline

**Table Thermodynamic Analysis of Impact of Inlet Air Cooling on gas turbine**

PARAMETERS	MAXIMUM	MINIMUM
temperature contour	3.694e+002	3.69e+002
temperature vector	5.014e+002	3.378e+002
pressure vector	2.045e+000	6.793e-001
velocity vector	1.849e+000	1.212e-002
temperature plane	5.001e+002	3.070e+002
temperature stream line	5.003e+002	3.883e+002
pressure streamline	2.376e+000	4.45e-001
velocity streamline	1.817e+000	1.873e-002

**DISCUSSIONS:**

The variation of the efficiency with respect to temperature at the compressor inlet with evaporative inlet cooling. also with rise in temperature the efficiencies of simple, intercooled and the reheat cycles shows slight increment as compared to the previous i.e. without inlet evaporative whereas regenerative cycle shows slight decrement but not as much in the previous one. As the temperature at the inlet to the compressor

increases the density of air decreases accordingly and to maintain the constant turbine inlet temperature the required input to the combustion chamber increases evaporative inlet cooling. The following conclusions have been drawn from the work: Performance curves shows that the pump work for the evaporative inlet cooler is in accordance with the mass flow rate of water, Performance curves shows that the specific output of the cycles slightly increases at evaporative inlet cooling.

**Conclusion:**

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

Inlet air cooling enables to increase the turbine inlet temperature even by up to 100°C yielding high efficiency without the need to go for improved blade material.

The present model involves the analysis of four configurations of the gas turbine cycle with evaporative inlet cooling. The following conclusions have been drawn from the work: Performance curves shows that the pump work for the evaporative inlet cooler is in accordance with the mass flow rate of water, Performance curves shows that the specific output of the cycles slightly increases at evaporative inlet cooling

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