International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 02 Issue: 05 May 2024
Page No: 1318 - 1326
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2024.0182

Power Augmentation of Gas Turbine Using Exhaust Flue Gas Operated Vapor Absorption Machine

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Abstract
Industrial gas turbines (GT) that operate at constant speed are constant-volume-flow combustion machines. As the specific volume of air is directly proportional to the temperature, an increase in air density results in a higher air mass flow rate at low air ambient temperatures. This results more mass of air is now passes through same volume gas turbine space. Consequently, the gas turbine power output increases proportionally with the increase in air mass flow rate. For geographic regions where warm and humid months are predominant throughout the year, significant power loss occurs during these months, and a higher rate of expensive fuel is fired at reduced power output. A gas turbine inlet air cooling technique is a useful option to enhance GT output. One of the innovative options for power augmentation of gas turbine is inlet air conditioning using a vapor absorption machine (VAM). Using VAM for GT intake air conditioning has the advantage over other systems in that it can be operated from waste heat. Many gas turbine machines, particularly natural gas pumping stations, are operated without heat recovery steam generator (HRSG) or heat recovery option. Valuable heat energy is escaped with exhaust flue gas in these systems. This paper demonstrates how GT exhaust waste heat can be utilized for its own power generation enhancement. In this study, a flue gas-based vapor absorption machine is selected for cooling the inlet air of a 26 MW gas turbine, which is used to drive the booster compressor of a natural gas pumping station. The capacity of the VAM for the required cooling effect has been calculated. The expected GT power enhancement from intake air gas conditioning has also been estimated in this paper.

Keywords: *Gas Turbine (GT); Vapor Absorption Machine(VAM); Energy Conservation; Heat and Mass Balance (HMB); Thermal Output.*

1. Introduction

Gas turbines (GT) are constant-volume machines, i.e., air intake is limited to a fixed volume, regardless of ambient air conditions. As the temperature of the air rises, its density falls. Thus, although the volumetric flow rate remains constant, the mass flow rate is reduced as the temperature of the air increases. This results in a reduction in power output, as power output is proportional to mass flow rate figure 1. The conversion efficiency of the GT also falls as the air temperature rises because more power is required to compress the warmer air.

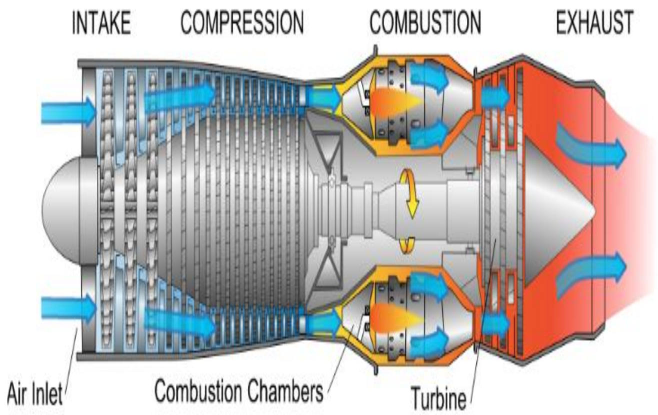

Figure 1 Gas Turbine

(Source: www.energyeducation.com) To explain the relationship, we need to link together a few insights.

- A gas turbine is a fixed-volume machine. You can only squeeze a fixed volume of air through the compressor and turbine. [2]
- The density of air increases when it is cold. Colder air means more mass of air in the same amount of volume. [2]
- The amount of power generated in the turbine increases with a higher mass of air flowing through it. [2]

When it gets hot, the opposite effect occurs. Power output decreases due to less mass flowing through the turbine. Ambient temperature also has an effect on the compressor. Colder air improves compressor efficiency. This means the compressor consumes less power, leading to more power being supplied to the generator.

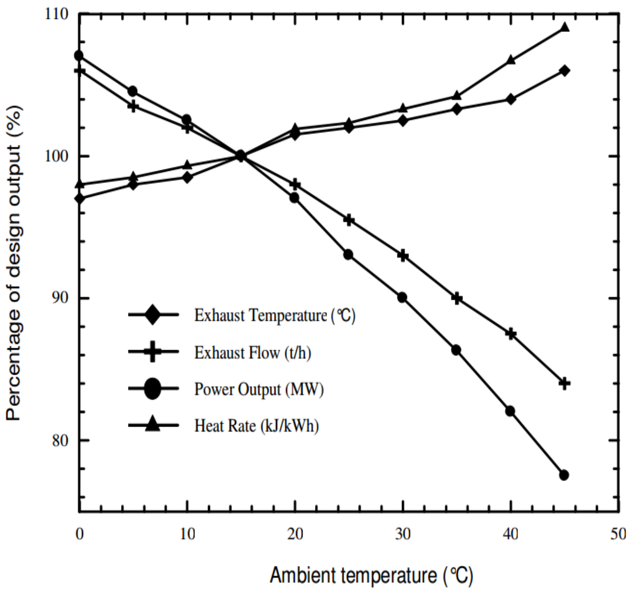

Figure 2 Effect of Ambient Temperature On Gas Turbine Performance

De Sa & Zubaidy (2011) proposed an empirical relationship for a 265 MW gas turbine. This gives us a rough rule of thumb of a 1% efficiency reduction and a 5% reduction in output for every 10 °C change. [3] For every K (Kelvin) rise in ambient temperature above ISO conditions, the gas turbine loses 0.1% in terms of thermal efficiency and 1.47 MW of its gross (useful) power output. [3] As per the thermodynamic principle of the ideal gas law, increasing the air density increases the mass flow rate. By ignoring the additional mass flow from the fuel, an ideal gas's mass flow rate is:

$$m = P1V1 / RT1, [1]$$

Where m is the mass flow rate, P is the pressure, R is the gas constant, T is the temperature, and V is the volumetric flow rate.

$$m_a h_a + m_{fuel} h_{fuel} = m_{fuel} h_{flue} + \frac{POgen}{Ngen}, [5]$$

Where

- M_a, m_{fuel} = Mass flow rate of air and fuel, respectively
- h_a, h_{fuel} = Enthalpy of air and fuel on unit mass basis, respectively
- h_{flue} = Enthalpy of flue gas on per unit mass of fuel basis
- PO_{shaft} = Power output of shaft after gear box
- N_{gen} = Efficiency of Gear Box

As per mass balance equation shown above, power output is a linear proportion of mass flow rate of air which is inverse function of temperature. As the inlet air temperature increases, such as on hot summer days, the capacity of the turbine decreases. If the inlet air is cooled to a lower temperature, the power increases along with increased efficiency (decreased heat rate). The cycle efficiency, η, can be expressed in terms of the isentropic compression process from compressor inlet temperature, T1, to compressor outlet temperature, T2, as follows:

$$\eta = 1- (T_1/T_2)$$, where η is thermodynamic efficiency. [1]

By decreasing T1, the efficiency increases. The effect of ambient temperature on the power output and efficiency of gas turbines. [1] Gas turbine site performance is directly affected by inlet air density and air environmental conditions figure 2. As explained above, the performance of GT improves with a lower inlet air temperature. Considering the above thermodynamic facts, to enhance the performance of the GT, in this project, the inlet air temperature is controlled close to ISO condition using the VAM.

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2. Objective and Methodology

The main objective of the literature is to analyze the power output of gas turbines under actual site conditions and after an air conditioning system has been implemented. For evaluation purposes, gas turbine data is taken from an actual gas turbine installed in one of the petroleum gas processing units for the pumping of crude gas from one point to a further located station. A gas turbine is used as a prime mover to drive a gas compressor to boost gas pressure up to 45 bar for gas transportation. In the existing installation, the exhaust of the gas turbine is allowed to escape through the chimney to the atmosphere without heat recovery. Legal regulation and guidelines barred the establishment of thermal heat recovery-based power generation and the trading of excess electricity generated by the grid. The objective of this study is to demonstrate the idea of utilizing waste heat recovery to enhance the power output of the gas turbine itself, thus saving some expensive fuel for the same power output. For this, the inlet air of the gas turbine is cooled closer to ISO conditions (say, 15°C) via the VAM system air conditioning system, which is operated through GT exhaust flue gas energy. In the proposed system, heat from hot flue gas is utilized to drive the VAM generator of the machine [4].

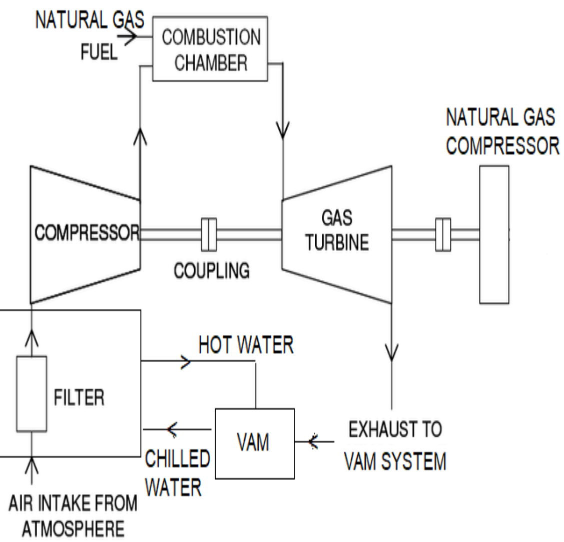

Figure 3 GT Block Diagram with Proposed Modification

The minimum temperature required to operate a flue gas-operated VAM generator is 325 to 350 °C, and the existing gas turbine exhaust is available at 485 °C. Looking at the available heat potential in GT exhaust flue gas, the proposed VAM system of adequate capacity will suffice for the required cooling effect of GT inlet air conditioning in the range of load. In this study, it is proposed to source high-temperature exhaust gas from the GT exhaust duct to operate the VAM system generator. Chilled water from the evaporator will be fed to the GT intake air conditioning system for air cooling [5]. The proposed scheme of block diagrams is as shown in Figure 3

3. Gas Turbine Performance Without Chiller

3.1 Plant Overview

A typical 26 MW GT unit with an open-cycle configuration is considered for the study. The site ambient condition is selected as 28°C and 35% relative humidity (RH). Table 1 A GT is selected from GE Model No. PG5371 (PA), which has an output of about 26 MW [6. The fuel used for the above plant is natural gas. The GT design data and site condition have been shown in Table 2.

Table 1 Gas Turbine Design Data

SR. NO.	PARAMETER	UNIT	VALUE
1	Gas Turbine Make	GE Power System	
2	Gas Turbine, Sr. No.	PG5371 (PA)	
3	ISO Base Rating	KW	26,070
4	Heat Rate	kJ/kWh	12,721
5	Exhaust Flow	kg/s	123.88
6	Exhaust Temp	°C	485
7	Pressure Ratio		10.6
8	Gas Turbine Efficiency	%	94.12

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Table 2 Site Ambient Condition Data

SR.NO.	PARAMETER	UNIT	VALUE
1	Barometric Pressure	bar	1.003
2	Relative Humidity	%	35
3	Ambient Temperature	°C	28
4	Air Density	kg/m^3	1.155
5	Air Enthalpy	kJ/kg	49.4
6	Specific Heat	kJ/kg. °C	1.006

3.2 Heat and Mass Balance Calculation of Gas Turbine at Site Condition

Table 3 Heat and Mass Balance Calculation of Gas Turbine at Site Condition

SR.NO.	PARAMETER (**Fuel Data**)	UNIT	VALUE
1	Fuel Type	Natural Gas	
2	Fuel Firing Rate (Flow)	kg/s	1.85
3	NCV of the NG	kJ/kg	45728
	Compressor Performance Data		
1	Compressor Air Inlet Flow	kg/s	115.87
2	Compressor Ratio	bar	10.60
3	Compressor Discharge Pressure	bar	10.64
4	Constant for Compression (C_P/C_V)	Ratio	1.40
5	Specific Heat of Air at Compressor Exit	kJ/kg. °C	1.02
6	Compressor Discharge Temperature Theoretical	°K	591.19
7	Compressor Discharge Temperature Theoretical	°C	318.04
8	Compressor Air Outlet Temperature. Actual	°K	627.04
9	Compressor Air Outlet Temperature. Actual	°C	353.89
10	Compressor Power Consumption	kW	38386.36
	Combustor Performance Data		
1	Combustor I/L Temperature	°C	353.89
2	Combustor Flue Gas Specific Heat at Average. Temperature	kJ/kg. °C	1.33
3	Total Flue Gas Flow In Combustor	kg/s	117.73
4	Combustor Power	kW	84844.21
5	Combustor O/L Temperature	°C	895.48
	Expander Performance Data		
1	Expander I/L Temperature (Controlled)	°C	895.48
2	Total Flue Gas Flow In Expander	kg/s	117.73
3	Expander O/L Temperature	°C	485.00
4	Expander Flue Gas Specific Heat at Average. Temperature	kJ/kg. °C	1.299
5	Expander Work	kW	62806.59
6	Expander Net Output	kW	24420.23
7	GT Losses (Pressure Difference Loss + Combustor Loss + Friction Loss + Gear Box Loss + Radiation Loss)	%	7.00
8	Net Power Output	kW	22710.81

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A heat and mass balance (HMB) calculation in the table 3. shows every performance parameter of a GT, including power output, for a given site condition. Normally, a heat and mass balance calculation utilize the balance of all input output process streams of energy and mass based on temperature, pressure, volumetric or mass flow rate, and enthalpy. The mathematical and calculated output of HMB at site conditions obtained from calculations is shown in the table 4. The plant's gross power output at site condition is about 22.71 MW. The selected GT was from PG5371 (PA), with an ISO output of 26.07 MW. However, these parameters can be further improved by the application of the VAM system in GT inlet air conditioning.

4. Gas Turbine Performance with Vapor Absorption Matchine (Vam)

4.1 Waste Heat Recovery Potential Calculation in Gas Turbine

Waste heat is energy that is not utilized and must be discarded in the environment due to process constraints.

Table 4 Waste Heat Recovery System (WHRS) Potential Calculation of GT Exhaust Flue Gas

SR.NO.	PARAMETER	UNIT	VALUE
1	Exhaust Flue Gas temperature	°C	485.00
2	Exhaust Flue Gas Flow	kg/s	117.73
3	Specific Heat with Exhaust Gas	kJ/kg	1.299
4	Exhaust Flue Gas Temperature	°C	150
5	Specific Heat of Exit Gas from WHRS	kJ/kg.°C	1.045
6	Heat Transfer Potential	kJ/s	46236.3
7	Considering Overall Heat Transfer Efficiency	%	90
8	Actual Heat Transfer Potential	kJ/s	41612.69

Recovering waste heat can be conducted through various heat recovery technologies. In our proposed recovery model, the VAM is used to operate with exhausted energy from GT. Currently, several manufacturers have developed the technology for their VAM systems to operate in harsh conditions of high temperature and high gas velocity [7]. Thus, it is feasible to utilize market available technologies for waste heat recovery to operate a VAM system to generate chilled water for further use in cooling the inlet air of gas turbines. The available thermal energy potential has been calculated and shown in Table 4

4.2 VAM System Modeling

Chilled water generated from the VAM system is utilized to condition the inlet air. A chilled water cooling coil with adequate surface area is needed to lay down in the GT intake manifold. The cooling capacity of the VAM system required to achieve inlet air cooling up to ISO conditions has been calculated below. Schematic diagram of the VAM system with GT as shown in figure 4.

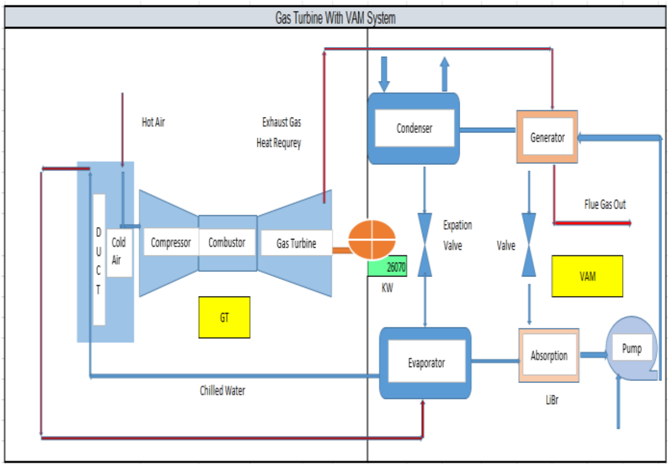

Figure 4 Schematic Diagram of the VAM Installation in FG Duct with Gas Turbine Air Intake System

4.3 Capacity estimation of VAM

First of all, we have to estimate the available energy potential in waste heat recovery to generate the cooling effect that has to be available in VAM. The next actual cooling capacity required at site

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https://doi.org/10.47392/IRJAEH.2024.0182

conditions at full load is determined. To determine the capacity of VAM required in our case, the mass flow rate of air at intake and its temperature-associated enthalpy are required. This will estimate the cooling requirements of the system.

Table 5 Available Potential with GT Exhaust Gas

SR. NO.	POTENTIAL SYSTEM OF HEAT RECOVERY	UNIT	VALUE
1	Proposed Coefficient of Performance of VAM (Considering Single Effect VAM System)	-	0.8
2	Cooling Effect Potential	kJ/s	33290.15
3	Cooling Effect Potential	TR	9465.89

4.4 Chilled Water Capacity Estimation

The cooling capacity of the VAM is estimated based on the inlet air temperature at site conditions, which is 28°C in our case. That needs to be cooled to 15°C, near the ISO condition of the turbine. The estimation is given below in Table 5. In general, one ton of refrigeration is equal to 3.52 KW. Total heat available for cooling can be estimated using the heat transfer formula: Qair = Mair × Cair × (Tout-Tin). Where Qair is the heat load during the air-cooling process considering dry air intake in KW, Mair is the mass of dry air [8] at intake of GT in kg/s, Cair is the specific heat of air in kJ/kg °C, and Tout –Tin is the difference between the air inlet and outlet temperature = 28-15 = 13 °C.

Table 6 Calculation of VAM Flow Capacity

SR. NO.	PROPOSED SYSTEM OF HEAT RECOVERY	UNIT	VALUE
1	Mass Flow Rate of Dry Air at inlet of GT	kg/s	115.87
2	Inlet Temperature	°C	28
3	Conditioned Air Temperature	°C	15
4	Specific Heat of Air at Inlet Temperature	kJ/kg. °C	1.006
5	Cooling Effect Required	kJ/s	1515.45
6	Cooling Effect Required in TR	TR	430.91
7	VAM TR Rating Required	TR	500

4.5 Heat and Mass Balance of After Using VAM System in GT

The heat and mass balance (HMB) of the GT unit with the VAM air conditioning system is calculated below Table 6. From the above calculation output, the total power output of the GT is about 24.63 MW with the VAM-based inlet air cooling system. GT power output of 24.63 MW after VAM system installation is enhanced by 1.86 MW from the previous power output of 22.71 MW operated in the same site condition table 7. The power output of the GT is increased due to an increase in the air mass flow rate.

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Table 7 **Calculation of Gas Turbine Output with the VAM System**

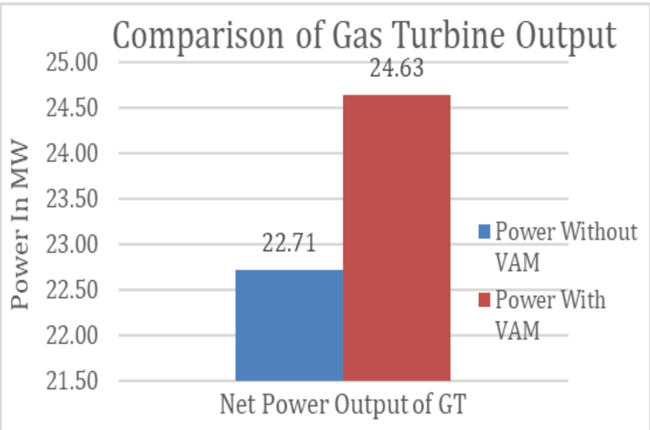
SR.NO.	PARAMETER	UNIT	VALUE
Fuel Data			
1	Fuel Type	Natural Gas	
2	Fuel Firing Rate (Flow)	kg/s	2.015
3	NCV of the NG	kJ/kg	45728
Compressor Performance Data			
1	Compressor Air Inlet Flow	kg/s	121.84
2	Compressor Ratio	bar	10.60
3	Compressor Discharge Pressure	bar	10.74
4	Constant for Compression (C_P/C_V)	Ratio	1.40
5	Specific Heat of Air at Compressor Exit	kJ/kg. °C	1.022
6	Compressor Discharge Temperature Theoretical	°K	565.67
7	Compressor Discharge Temperature Theoretical	°C	292.52
8	Compressor Air Outlet Temperature. Actual	°K	599.97
9	Compressor Air Outlet Temperature. Actual	°C	326.82
10	Compressor Power Consumption	kW	38524.07
Combustor Performance Data			
1	Combustor I/L Temperature	°C	326.82
2	Combustor Flue Gas Specific Heat at Average. Temperature	kJ/kg. °C	1.323
3	Total Flue Gas Flow In Combustor	kg/s	123.85
4	Combustor Power	kW	92121.24
5	Combustor O/L Temperature	°C	889.02
Expander Performance Data			
1	Expander I/L Temperature (Controlled)	°C	889.02
2	Total Flue Gas Flow In Expander	kg/s	123.85
3	Expander O/L Temperature	°C	485.00
4	Expander Flue Gas Specific Heat at Average. Temperature	kJ/kg. °C	1.2992
5	Expander Work	kW	65011.04
6	Expander Net Output	kW	26486.97
7	GT Losses (Pressure Difference Loss + Combustor Loss + Friction Loss + Gear Box Loss + Radiation Loss)	%	7.00
8	Net Power Output	kW	24632.88

5. Results and Discussion

Technical Analysis of the Inlet Air Cooling System

The basis of most design decisions is economics. Designing a system that functions properly is only one part of the engineer's task. The system must also be economical and show an adequate return on investment. Hence, for any modification to the existing project to be undertaken, it has to be economically sound and viable [9]. Therefore, this study also seeks to establish the economic viability of the modification work proposed. A comparison of GT performance parameters for both GTs with and without a VAM system is shown in the graph.

Figure 5 Comparison of GT Output Parameters with and Without VAM



The total net power output is increased by about 1.86 MW; the same is represented in the graphical form as shown in figure 5.

6. Economic Analysis of the Inlet Air Cooling System

The estimation of the total investment cost of the VAM system package and its payback period is required to verify whether the proposed project is financially viable. The capital investment cost consists of the costs incurred for procurement, erection, and site testing and commissioning. The operating cost includes the operation and maintenance of the system [10]. The payback period is one of the simplest investment appraisal techniques. This is defined as the time in which the initial cash outflow of an investment is expected to be recovered from the cash inflows generated by the investment.

Table 8 Calculation of Required VAM Capacity and Investment Return Payback Period in Month

SR. NO.	PARAMETER	UNIT	VALUE
1	VAM TR Rating Required	TR	500
2	Cost of the VAM System with Chiller Coil in GT Duct	Rs (Lakh)	300.00
3	Extra Power Generated after Maintaining Design Condition near to ISO	MWh/Yr.	109011.89
4	Generation Cost	Rs/kWh	10
5	Net Saving	Rs/Yr.(Lakh)	109.01
6	Simple Payback	Month	4

It is estimated that the total project cost for retrofitting or installing the VAM system in the plant is about Rs. 300.00 lakhs. This is inclusive of interest during construction (IDC) and financing costs (FC). Net power generation has been calculated by considering that the plant will operate with the VAM for 200 days of 24-hour operation during the summer months with a plant load factor (PLF) of 80% and the additional cost obtained due to the sale of additional power generated per annum was estimated to be about Rs. 1090.11 lakhs by considering the electricity selling price of about Rs. 10 per kW. The estimated payback period is about 4 months for a total capital investment of Rs. 300.00 lakhs, considering that the proposed VAM system will operate only for 200 days during peak summer months' table 8. The same will be reduced if the system is operated more than the considered operating day.

Conclusion

The performance of a gas turbine as well as the gas

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turbine power plant mainly depends on the inlet air temperature. A reduction in the temperature of the air will increase the power output due to the increase in density and mass flow rate of the air. It also allows for the injection of more fuel, keeping the turbine inlet temperature (TIT) constant at the permissible limit prescribed by the original equipment manufacturer (OEM). By applying the VAM system, a decrease of about 13 °C in the inlet air temperature will increase the net power output by approximately 1.86 MW. The total investment cost for this will be Rs. 300 lakhs, with a payback period of 4 months.

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