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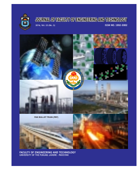

ENHANCEMENT IN OVERALL THERMAL EFFICIENCY OF A GAS TURBINE POWER PLANT USING COMBINED CYCLE SYSTEM

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Abstract

The gas turbines are one of the major resources of power generation in the world and their usage is increasing day by day. Although the gas turbines have several advantages over other systems (such as high power to weigh ratio, high rotational speed or fast activation capabilities) but they still waste the energy in the form of high temperature exhaust gases coming out of the gas turbine which pollute the atmosphere and affect the environment. A waste heat recovery system (WHRS) installed at Gas turbine exhaust helps not only to reduce the exhaust temperature of these gases emitting from the uptake into the atmosphere but also enables to produce useful steam for various processes.

The air mass flow rate which enters the compressor has a direct relation with the performance of gas turbine power plant. The volumetric efficiency of the gas turbines decreases with rise in the temperature of the inlet air. The increase in temperature will reduce the density which results in the reduction of gas turbine efficiency. In the present work the steam produced from WHRS has been used in the vapor absorption system of refrigeration. The refrigeration system is utilized to cool the air at the entry of the gas turbine compressor power plant. It was observed in gas turbine power plant that there is a 10% increase in thermal efficiency.

Keywords: Absorption Chiller, Compressor, Gas Turbine, Vapor Absorption System, Waste Heat Recovery System

1. Introduction

Use of power has a direct influence on the living standard and prosperity of a nation. Sources of inexpensive energy are required for the development of the industries and to make a good improvement in our way of life. A power Plant plays an importance in residential as well as industrial sector, as one of the basic needs of today's life is electricity. Many large industries produce electricity by their own power plants, whereas residential sector & small industries usually buy electricity either from government or from independent power producers.

Gas turbine employs gas flow as medium of working fluid which transforms the heat energy into mechanical energy. The gas turbine has less efficiency especially at part load and can be increased by using combined cycle [1]. During summer at the middle of the day at kingdom of

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Saudi Arabia the maximum electric power demands double of the off peak demand. Due to this condition there would be decay in combustion turbine performance profile as their output power will decrease with the increase in the temperature of inlet air [2]. Another example is Turkey where almost everywhere there is a loss in the production of electricity during the periods when the temperature raises from15 °C. Base on the Turkey regions, the lost rates and standard ambient temperature changes from 1.67% to 7.22%. When the temperature of the inlet air is reduced to 10 °C, the generation of electricity will boost around 0.27 to 10.28% [3].

Because of the thermodynamic limitations by the second law, most of the rejected heat is unavailable energy that has an effect on the characteristics of the steam power cycle which is classified as waste heat. The balance of the rejected heat results from the losses inherent in the energy conversion processes. There are many ways to utilize the waste heat coming out of the gas and steam turbines such as producing steam for industrial purposes, and using to run absorption chillers.

The main aim of this research is to study and analyze the working of gas turbine and effect of cooling the inlet air (with some cost effective means) entering in to the compressor on the overall efficiency of gas turbine. Cooling the air which enters the compressor increases the density of the air flowing into the plant, since denser air results in higher mass flow rate and the ability to burn more fuel, thereby increasing the power output. As the compressor work is directly proportional to the ambient temperature of air. Therefore lowering the inlet temperature of air reduces the specific input of the compressor. Two by third of the power produced by the gas turbine is used to run the compressor. The decrease in ambient temperature results in higher output power and lower input power to compressor which ultimately increase the turbine efficiency.

2. Materials and Methods

2.1. Gas Turbine Data for Experimental Work

The specification of the gas turbine used the in the present research work are given in Table 1.

Table 1. Specification of gas turbine of capacity 3.5 MW Solar Centaur (C – 40)

S/N			S/N		
1	Manufacturer	Turbo Mach Switzerland	8	Continuous rating at power shaft at ISO conditions	3,721 kW (gas fuel)
2	Model	Solar Centaur- 40	9	Compression ratio	9.5: 1
3	Fuel type	Natural gas or liquid fuel	10	Turbine rotational speed	14,951 RPM
4	Turbine Design	Open cycle, single shaft turbine cold – end drive	11	Turbine air inlet flow at ISO conditions	18.27 kg/sec
5	Compressor	11 stage axial flow	12	Heat Rate at ISO conditions	12,200 kJ/kWh
6	Turbine	3 stage, air cooled first stage power turbine	13	Exhaust gas temperature at ISO conditions	434ºC
7	Combustor	Annular with 10 fuel injectors	14	Exhaust gas mass flow at ISO conditions	18.61 kg/sec

2.2. Experimental Setup

The Centaur-40 gas turbine is used for industrial service in electric power generation applications; it is a single shaft, axial flow design consisting of air inlet assembly, eleven stage compressor with fixed and variable vane assemblies, compressor diffuser assembly, combustor assembly with annular combustion chamber, three stage turbine assembly, turbine exhaust diffusers assembly and exhaust system connector. These major components are maintained in accurate alignment by mating flanges with pilot surfaces and they are bolted together. The turbine drives the compressor, gear unit and driven equipment from the front end of the engine, utilizing the compressor rotor as the engine output shaft. Access to the compressor is provided by removal of either side of the vertically split compressor case. With one of the compressor case halves removed, the entire 11 stages of rotor blade and stators are exposed for inspection, cleaning, or replacement. Compressor consists of inlet air assembly which has annular opening covered with mesh screen, to prevent the entry of large objects into the turbine air inlet. The compressor variable vane assemblies consist of the inlet guide vane assembly, the stator assemblies, and the electrically controlled and hydraulically operated variable vane control actuator. The forward end of the inlet guide vane assembly is bolted to the air inlet housing. The rear end of the second stage stator assembly is mounted to the compressor case housing. Figure 1 shows different parts of C – 40 Gas Turbine, where compressor is on the left side.

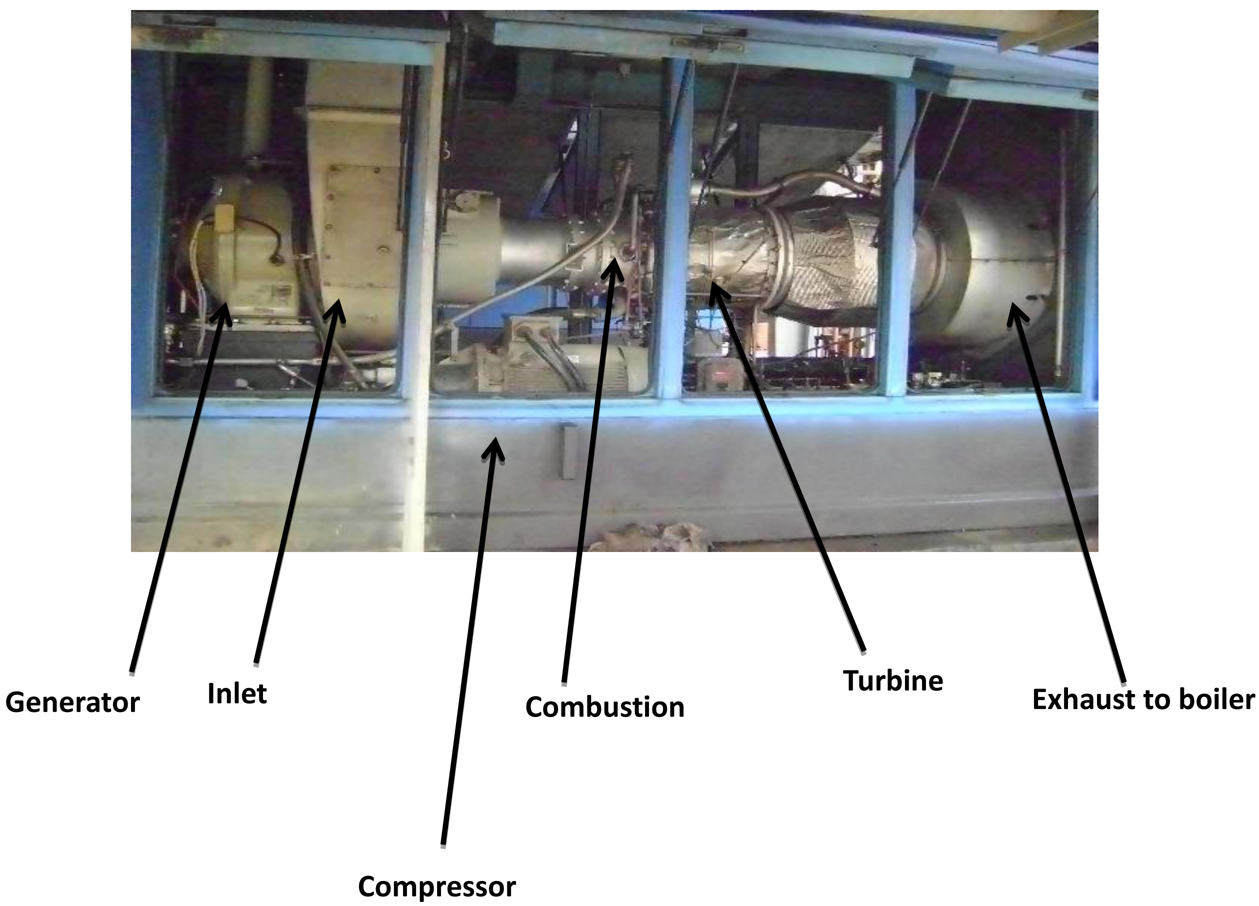

Figure 1. Solar Centaur- 40 Gas Turbine

2.2.1. Inlet Air Cooling of Gas Turbine

Cooling gas turbine inlet air entering to the compressor, however, increases the density of air and mass flow through the turbine. Gas turbines operate with a constant volume of air, but the power output of the gas turbine depends upon the mass flow rate of air. The density of the warm air is less than the cold air and it results in lower power output. Compressor has to do more work to compress the warm air than cold air and thus increasing internal losses [4]. Figure 2 shows the inlet air cooling system for gas turbine.

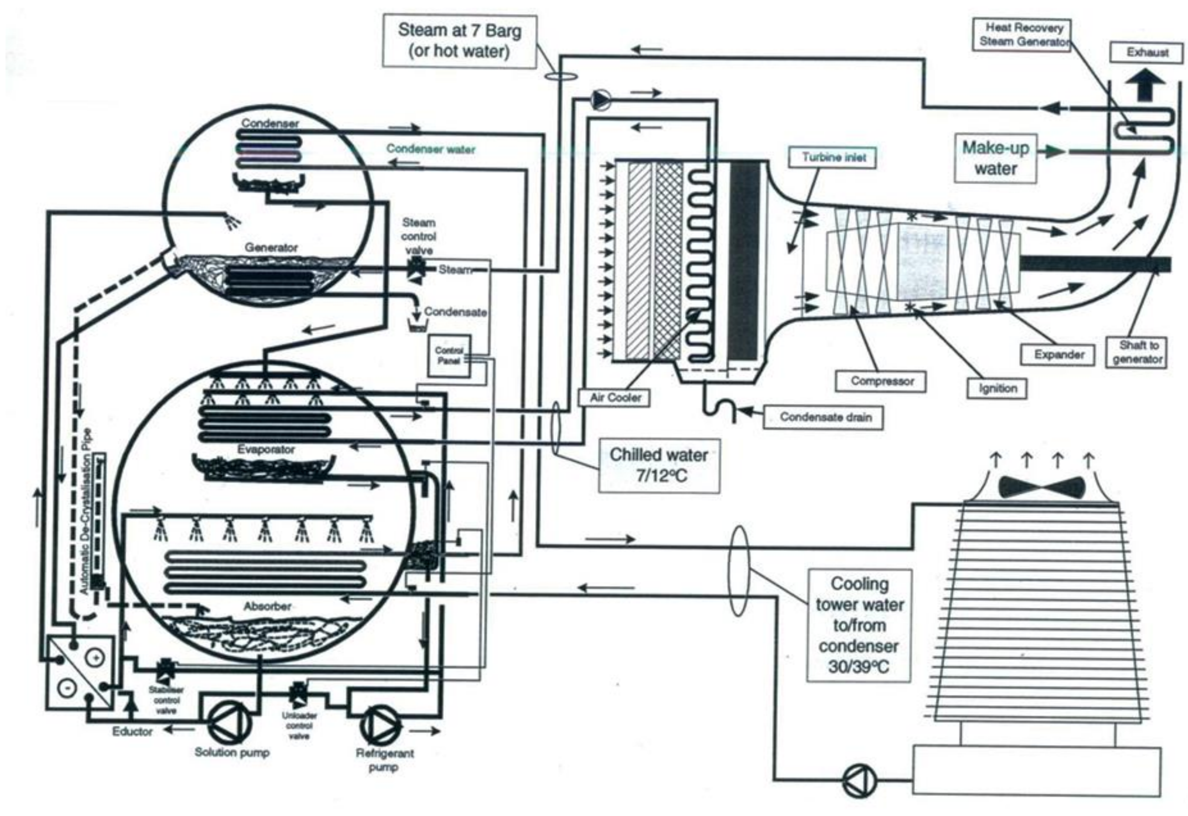

Figure 2. Inlet air cooling system

2.2.2. Absorption Cooling System

We can match the absorption cooling systems to the mechanical cooling systems with an exception that in this case absorption chillers are used instead of mechanical chillers. In absorption chillers primary source of energy is thermal energy (hot water/ steam), and require much less electric energy than the mechanical chillers. Absorption cooling systems can be used to cool the inlet air to about 10°C. These systems can be used with or without chilled water thermal energy systems. Absorption chillers can be single-effect or double-effect chillers. The benefit of the system is that it has extremely standby power, and its major disadvantage is that as compared to other systems even mechanical refrigeration systems, its capital cost is much higher. One of the most successful absorption chiller's applications is in thermal power plants. These plants have excess of thermal energy available and it is better to convert this energy into electricity, which has higher value, for the user profit [5].

2.2.3. Waste Heat Recovery System

The exhaust gases coming out of the gas turbine have high temperature and in order to recover the thermal energy from these gases which are passed through heat exchanger. These types of heat exchangers will fall under the air-to-water heat exchanger category. In this type the waste gas will pass over some form of fin and tube of heat exchanger surface while the heat which is gained from the waste gas is used to prepare hot water/ steam [6].

2.3. Methodology

The performance of the Solar Centaur – 40 Gas Turbine has been observed at different ambient temperatures. The effect of ambient temperature on its power output, heat rate, fuel mass flow rate has been analysed. The calculations are made to calculate the density of the air and specific gas consumption at different ambient temperatures. Gas law is used to calculate the density of the air. The cooled water is introduced at the inlet of the compressor to reduce the temperature of the incoming air. The effect of inlet air cooling on the overall performance of the gas turbine has been discussed. Absorption chiller is used to produce the cooled air and the amount of the steam record to run the chiller is drawn from Waste heat recovery system. The gases coming out from the turbine are introduced into waste heat recovery system and useful amount of steam is produced. Mathematical calculations are done to calculate to know the amount of steam produced against running power of the turbine.

3. Results and Discussion

The performance of the turbine at different ambient temperatures is shown in Table 2. It can be observed that with increasing temperature the power output of the turbine decreases which results in lower turbine efficiency.

Table 2. Nominal Performances of 3.5 MW Gas turbine (C- 40)

Ambient Temperature ºC	15	20	25	30	35	40	45
Load %age	100	100	100	100	100	100	100
Net Output Power KW	3331	3209	3087	2961	2839	2722	2612
Fuel Flow GJ/Hr	44.0	42.7	41.4	40.1	39.0	38.0	37.1
Heat Rate KJ/KW.Hr	13209	13307	13411	13543	13737	13960	14203
Efficiency %age	25.20	24.12	23.04	21.861	20.66	19.5	18.4
Exhaust Gas Flow Kg/Hr	64912	63642	62373	61000	59596	58189	56771
Exhaust Gas Temperature ºC	441	443	445	449	453	458	463

3.1. Effect of Ambient Temperature on Density and Mass Flow Rate of Air

Cooling gas turbine inlet air entering to the compressor, however, increases the density of air and mass flow through the turbine. With increasing temperature from 15 to 45 °C the density was decreased from 1.22 kg/m^3 to 1.09 kg/m^3 as shown in in Fig. 3. The mass flow rate was also decreased from 19.66 kg/sec at temperature of 15 °C to 17.87 kg/sec at 45 °C as shown in Fig. 3. Figure 4 indicates that at 45 °C the power output is 2612 KW and by reducing the inlet temperature it increases up to 3331 KW. Reducing the temperature from 45 °C to 15 °C result in high pressure ratio and low work of compression.

Reducing the work of compression is important, for when hot gases from the combustor expand in the gas turbine; roughly 2/3 of the mechanical work is used to drive the air compressors, while only one-third of the mechanical work is available for useful power output. Compression ratio has also effect on the performance of the gas turbine. Theoretically, higher compression ratios will result in higher thermal efficiencies. In practice, however, compression ratios are limited by the costs associated with the additional compressor stages required to achieve them. In addition, higher compression ratios result in higher temperatures of the compressed inlet air (because of the heat of compression). If compression ratios are too high, an inter-cooler may be required to minimize the temperature of the compressed inlet air. Thus, cooling inlet air during periods of high ambient temperatures is a cost-effective means of increasing the power output of the generator, while also reducing the heat rate of the combustion turbine.

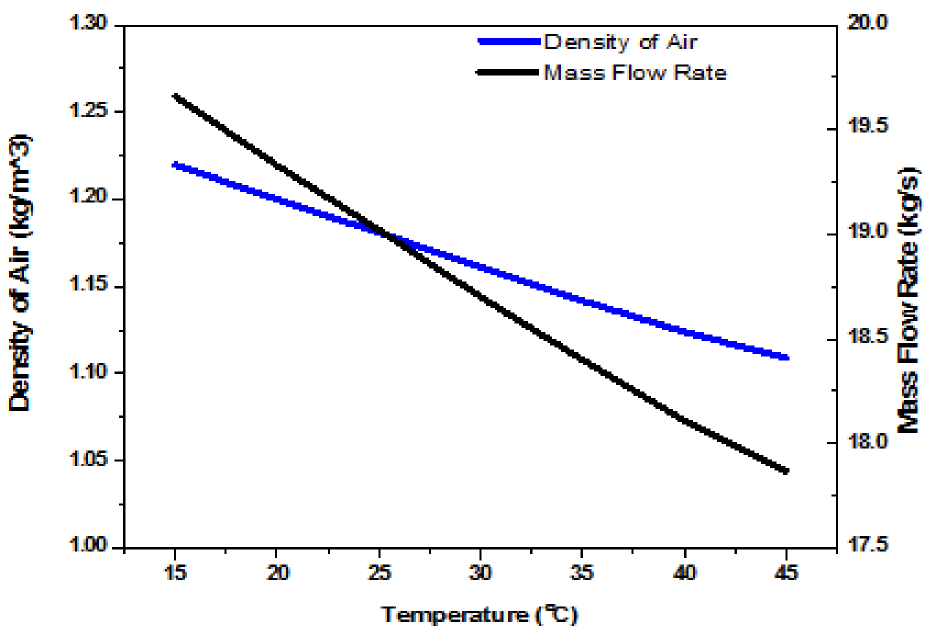

Figure 3. Graph between Density, Mass Flow Rate of Air and Temperature

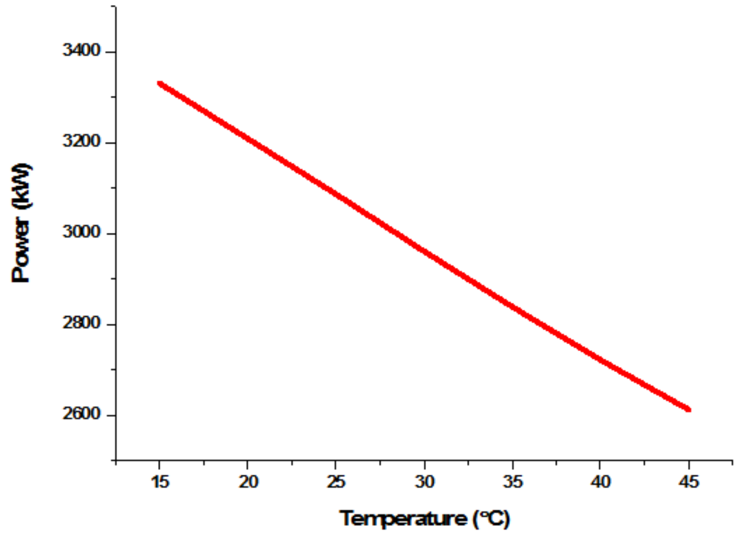

Figure 4. Graph between the Power Output of the Gas turbine and Temperature

3.2. Effect of Ambient Air Temperature on Heat Rate and Volume of the Gas

Heat rate is defined as the amount of the heat required to produce 1 KW of power. By cooling the gas turbine inlet air the heat rate is reduced from 14203 to 13209kJ/KW.hr, which enhances the combustion efficiency of the fuel (Fig 5). The value of specific gas consumption to produce 1KW-Hr power was found lower at 15 °C. 0.433 m^3 of the gas is required at 45 °C to produce 1 KW-Hr power which is about 7 % more than the amount of the fuel at 15 °C (Fig 5). Therefore cooling the air at inlet of compressor, results in fuel saving, this means more economical system.

Higher mass flow rate and lower heat rate affect the turbine efficiency. The efficiency of turbine at temperature of 45 °C ambient temperature was 18.4 %, whereas at 15 °C this efficiency goes up to 25 % (Fig 6).

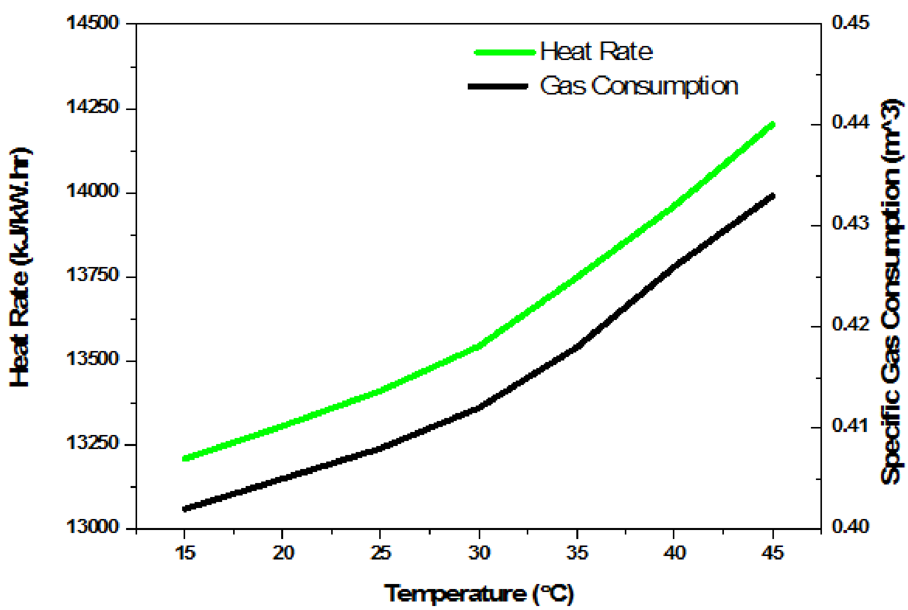

Figure 5. Graph between Heat Rate, Specific Gas Consumption and Temperature

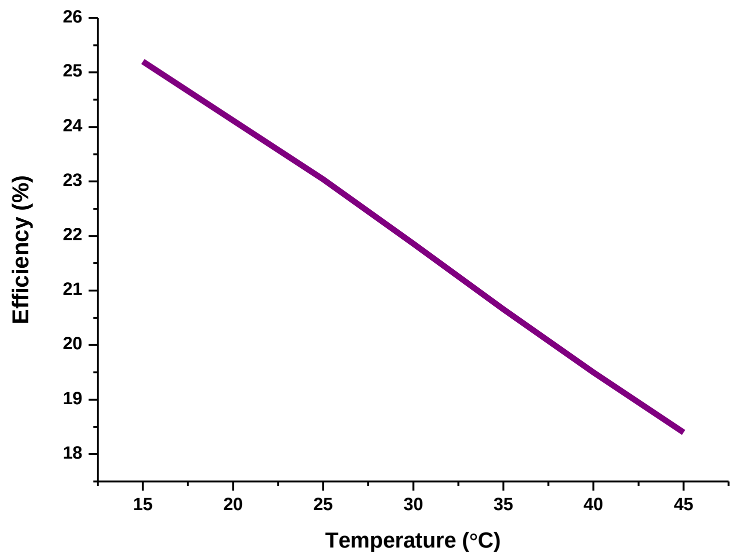

Figure 6. Graph between the Efficiency of Gas turbine and Temperature

4. Conclusions

The effect of ambient air temperature on the performance of Solar Centure – 40 Gas Turbine has been discussed. Performance characteristic of gas turbine (Solar Centaur C-40) is shown in the Fig 4. It shows that by increasing the ambient temperature to 45ºC there is decrease in gas turbine power output capacity. Cooling the inlet air to 15ºC increases the power output of the gas turbine. From the table given above and from the Fig 4 it can be observed that the power output capacity of gas turbine at 15ºC is nearly 27 % higher than its capacity at 45ºC. The efficiency was calculated on the basis of heat rate and it was concluded from the Table 1 as well as from the figure 6 that 10 % of efficiency improved by cooling the inlet air of compressor from 45 ºC to 15 ºC.

The gases coming out of the gas turbine have temperature of around 500ºC. By using the waste heat recovery system; this temperature was reduced up to 200ºC. The effect of thermal pollution at 200ºC is less than at 500ºC.This temperature gradient was used in the waste heat recovery boiler to heat the water from which steam can be produced. It can be concluded that 2.5 tons/hr steam could be produced from the exhaust gasses with the gas turbine operating at 1 MW. As the capacity of the gas turbine is 3.4 MW it means that if the gas turbine is running on full load then from the gases coming out of the Gas turbine steam up to 8 Ton/hr can be made.

5. Acknowledgement

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References

[1] Y.S.H. Najjar. “Efficient use of energy by utilizing gas turbine combined systems” Applied Thermal Engineering, Volume 21, Issue 4, 2001, Pages 407-438

[2] A.M. Al-Ibrahim, A. Varnham. “A review of inlet air-cooling technologies for enhancing the performance of combustion turbines in Saudi Arabia” Applied Thermal Engineering, Volume 30, Issues 14-15, 2010, Pages 1879-1888

[3] H. Erdem, S.H. Sevilge. “Case study: Effect of ambient temperature on the electricity production and fuel consumption of a simple cycle gas turbine in Turkey” Applied Thermal Engineering, Volume 26, Issues 2-3, 2006, Pages 320-326

[4] F.J. Brooks, **“**GE Gas turbine Performance Characteristics” of GE Power Systems Schenectady (http://www.up.farsscript.ir/uploads/13316846411.pdf) (accessed on February 01, 2009)

[5] Turbine Inlet Cooling Association, Turbineinletcooling.org

[6] www.Trigeneration.com (accessed on 15 January 2009)

[7] A. Abedin, **“**Should Summer De-rating & Lower Winter Part-load Efficiency of Gas turbine Combined Cycle Power Stations be accepted?” conference of Singapore International Convention and Exhibition Centre, Volume 2, 9 – 11, 1997.

[8] Thermal Energy Equipment. Waste Heat Recovery System (http://www.energymanagertraining.com/GuideBooks/2Ch8.pdf) (accessed on 20January 2009)

[9] A. Abedin, “Cogeneration System for Industrial Air-conditioning with Gas Engine Waste Heat Recovery” conference paper 8th HVACR Expo and Conference, February 23 – 25, 2001, EPB Expo Karachi.

[10] S. Boonnasaa, P. Namprakaia, T. Muangnapoh, “Performance improvement of the combined cycle power plant by intake air cooling using an absorption chiller” International Journal of Energy Volume 31, Issue 12, 2006, Pages 2036–2046.

[11] Data Provided by TURBOMACH and available at Nishat Mills Ltd Lahore. (accessed on September,2008).

[12] V.K. Attri, A.S.M. Kumar, “Performance Evaluation of Trigeneration Systems” International Journal of Emerging Technology and Advanced Engineering, Volume 4, Special Issue 1, 2014.

[13] Introduction to Gas turbines for Non- Engineers (Published in the Global Gas turbine News, Volume 37: 1997, No. 2) by Lee S. Langston, University of Connecticut and George Opdyke, Jr., Dykewood Enterprises.

[14] T.K. Ibrahim, M.M. Rahman, A.N. Abdalla “Improvement of gas turbine performance based on inlet air cooling systems: A technical review” International Journal of Physical Sciences Vol. 6 (4), pp. 620-627, 2011.

[15] A. Marzouk , A. Hanafib, “Thermo-Economic Analysis of Inlet Air Cooling In Gas turbine Plants” Journal of Power Technologies 93 (2) 2013, 90–99.