International Journal of Innovative Research in Engineering & Management (IJIREM)
ISSN: 2350-0557, Volume-4, Issue-3, May-2017
DOI: 10.21276/ijirem.2017.4.3.4

Improvement of Gas Turbine Power Plant Performance: A Review

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ABSTRACT

Gas turbine could play a key role in future power generation addressing issues of producing clean, efficient and fuel flexible power generation. In the field of energy generation, gas turbines have often been chosen in the past when fast start and shut down on demand is required. In this paper an attempt has been made to review research activities and studies carried out worldwide so far on gas turbine power plant. The historical development in chronological order has been presented first, followed by some fundamental features about gas turbine. This paper mainly reviews the effect of different operating parameters and atmospheric conditions on the performance of gas turbine power plant. Moreover, various studies based on the modeling and simulations have been reviewed. Research on gas turbines with evaporative coolers, heat exchangers and absorption chillers has also been assessed.

Keywords

Gas Turbine, Efficiency Enhancement, Evaporative Cooling, Turbine Inlet Temperature (TIT), Relative Humidity

1. INTRODUCTION

Coal based thermal power plants are still dominating the power sector in India. As it is known that the coal reserves are limited to their natural availability and also the expansion of coal mining is limited in India. It has been anticipated that Indian coal sector will face substantial shortfall in the production of coal in future. The degradation of the environment and the occurrences of different natural calamities due to the different pollutants emitted by the coal based plants are also of great concern. In case of gas based power plants, natural gas is used which is a clean fuel as compared to coal and can be used more efficiently in power generation. Gas based power plants are increasing more and more nowadays and the government of India is also encouraging gas based power plants because of their environmental advantages.

Gas turbine is also a kind of the internal combustion engine in which burning of the air-fuel mixture produces hot gases to run the turbine for the generation of mechanical power. In gas turbines, combustion occurs continuously as compared to the reciprocating internal combustion engines in which it occurs intermittently. Sumit *et al.* [1] shows the Current Scenario & Future Prospects in India. They also pointed out that the total design capacity of gas turbine power plants in India is about 26700 MW which is increased by 51.3% as compared to the year 2011 in which it was only 13710 MW and most of these are installed in Gujarat, Andhra Pradesh, Maharashtra, Tripura, Assam, Uttar Pradesh, West Bengal, Tamil Nadu, Rajasthan, Pondicherry, Karnataka, Kerala, Haryana, Delhi. Hence, in India the gas turbine plays an important role to produce energy. If different types of advanced materials for turbine blades, turbine wheels, compressor blades, combustor and also coating materials for sophisticated parts of turbine can be used, then the gas turbine power plants will be more efficient, reliable, and cost effective. Indian government is trying to establish more and more gas turbine power plants using advanced materials to combat the environmental problems arising from the power sector.

In India the production of natural gas presently is at the level of around 132.83 million metric standard cubic meters per day. The main producers or suppliers for natural gas in India are Oil & Natural Gas Corporation Limited, JVs of Tapti, Panna Mukta, Ravva, and Reliance Industries Limited.

The gas turbines are widely being used for producing electricity, operating airplanes and for various industrial applications such as refineries and petrochemical plants. In aircraft propulsion or drives for vehicles, gas turbines are chosen due to large power-to-weight ratio and power-to-volume ratio. Furthermore, for certain operating conditions, the cycle efficiency of gas turbine is higher compared to reciprocating engine. In the field of energy generation, gas turbines have often been chosen in the past when fast start and shut down on demand was required. This is especially needed for compensating peak loads during the daytime. In contrast, coal and oil firing steam power cycle or nuclear power plants are base-load machines since the start and the shut-down are much longer.

Gas turbines have been used for electricity generation in most of the countries around the world. In the early days, their uses were generally limited to generating electricity in the period of peak electricity demand. Gas turbine are ideal for application as they can be started and stopped quickly enabling them to brought into service as required to meet the peak electricity demand. However, due to the availability of natural gas at cheap price compared to distilled fuels, many countries around the world use large conventional gas turbine as base load unite, while small one to meet any shortage in available electricity supplies occurring during the emergency or peak electricity demand period. These systems, especially working in an open or simple cycle have the disadvantage of being least efficient and so the unit cost of generated electricity is relatively high.

The low efficiency of gas turbine plants is due to many factors which include operating model, poor maintenance procedures, age of plant, discrepancies in operating data, high ambient temperature and relative humidity. So, it is clear that these are the factors which directly or indirectly have an effect on the performance of gas turbine. The gas turbine engine has many advantages such as low investment costs, use-flexibility, and low emissions, no water consumption and short construction lead time. However, conventional industrial engines have low efficiencies.

The base gas turbine cycle has low thermal efficiency, so it is important to look for improved gas turbine cycles. Enhancement in the performance of gas turbine has become successful through raising the turbine inlet temperature (TIT) and compressor pressure ratio. The advancement in cooling technology and the development of new materials which can sustain high turbine inlet temperature have played an important role in this regard.

2. GAS TURBINE CYCLES

The Brayton cycle is a thermodynamic cycle named after George Bailey Brayton that describes the workings of a constant pressure heat engine, although it was originally proposed and patented by Englishman John Barber in 1791. It is also sometimes known as the Joule cycle.

There are basically two types of gas turbines (GT). One is open cycle GT and other is closed cycle GT. Sometimes, semi cycle GT is also used in particular applications. In open cycle high pressure air enters the combustion chamber where the fuel is burned at constant pressure. The gas with high temperature and pressure enters the gas turbine where it expands to ambient pressure and produces work. Some part of the power developed by the turbine is utilized in driving the compressor and other accessories and remaining is obtained as output power. Closed cycle operation is very much similar to open cycle the only difference is that the expanded air by the turbine is again used by the compressor. Closed GT is also more flexible with the fuels. Figure 1 shows the complete T-S diagram of a Brayton cycle. Brayton cycle is mainly composed of four processes. Out of these, process 1-2 is the isentropic compression process in the compressor. Process 2-3 is the constant pressure heat addition in combustion chamber. The process 3-4 is the isentropic expansion in turbine and finely process 4-1 is the constant pressure heat rejection.

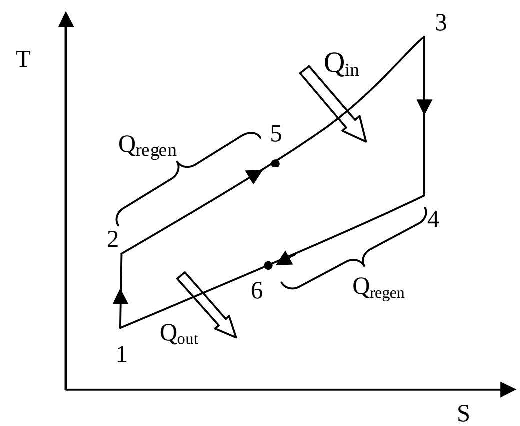

Figure 1. T-S diagram for a simple Brayton Cycle

It has high power to weight ratio, high reliability, and long life. Almost any hydrocarbon fuel from high-octane gasoline to heavy diesel oils can be used in the combustion chamber of the gas turbine. When the plant is operating at its peak load the stipulation of a quick start and take-up of load frequently are the points in favor of open cycle plant. One of the most important features of open cycle gas turbine power plant, except those having an intercooler, does not need cooling water. Therefore, the plant is independent of cooling medium and becomes self-contained.

3. AIM OF THIS PAPER AND NOVELTY

Some authors such as Olumayegun *et al.* [2] and Keller [3] have reviewed the development of closed-cycle GT for power generation. They attempted to establish the maturity of closed-cycle GT technology by highlighting the operating experiences of the early closed-cycle GTs using fossil fuel as heat source and air as working fluid. The present paper aims to provide a state-of-the-art assessment of the research activities and development of closed-cycle GT. The authors feel that for those with little knowledge of closed-cycle GT, this paper will give them an introduction of the relevant concepts necessary to achieve basic understanding. The past experiences and recent progresses in gas turbine technology have been reviewed in this paper. This will certainly give an outlook of the future research directions based on current developments to those already acquainted with the technology.

4. HISTORICAL DEVEOLOPMENT

A list of important events in the development of gas turbines is presented in table 1 in a chronological order. Keller patented the closed-cycle GT in 1935, at a time when the development of GT technologies was just emerging. Four years later, a closed-cycle GT named the AK-36 test plant, was built. In 1939, due to the commencement of the Second World War and the economic recession that followed, the research activities slowed down until in 1949 when the first industrial closed-cycle GT power plant was commissioned in Coventry, UK. With the successful operations of small, air based closed-cycle GT power plants in Europe, efforts were directed towards the design of plants with larger capacity.

It was found that the gas turbine plants with more than 30 MW capacity having helium as a working fluid were much more efficient than gas turbines having air as a working fluid. Helium could additionally be used as a coolant in HTGRs. The first helium based closed-cycle GT, with no output power generation,

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was developed in 1962 by James La Fleur which was used for driving a cryogenic air separator in the USA. Earlier in 1942, Keller had proposed the application of helium based closed-cycle GT to HTGRs with direct cycle. A tremendous growth has taken place in the field of gas turbines after the 1970s which has been further illustrated in the paper.

Table 1. History of Gas Turbine

1791	The first patent for gas turbine was proposed by John Barber of United Kingdom.
1904	A gas turbine project was attempted unsuccessfully by Franz Stolze in Berlin.
1906	A gas turbine was developed by Armengaud Lemale in France which comprised of a centrifugal compressor but with no useful power generation.
1910	The first gas turbine featuring combustion was developed (constant volume combustion) by Holzwarth. It was of 150 kW capacity.
1923	First exhaust gas turbocharger was developed to increase the power of a diesel engine.
1935	Keller and Ackeret patented the first closed cycle gas turbine in Switzerland
1939	World’s first gas turbine for power generation was developed by Brown Boveri Company, Neuchatel, Switzerland.
1962	The first helium based closed-cycle GT built for air liquefaction was developed by James La Fleur in USA.
1972	The biggest and the last air closed-cycle GT was built by Escher Wyss in Vienna.

5. PERFORMANCE REVIEW

Johnson [4] discussed the theory of evaporative cooling and described the application of wetted rigid media evaporative coolers to gas turbines. They studied the evaporative cooler design, installation, operation, feed water quality, and the causes and prevention of water carry over. Evaporative coolers were used with gas turbines to increase the density of the combustion air, thereby increasing power output. The air density increase was accomplished by evaporating water into the inlet air, which decreased its temperature and correspondingly increased its density. The water vapour that passed through the turbine caused a negligible increase in fuel consumption. Water used with evaporative coolers often contains dissolved solids such as sodium and potassium, which, in combination with sulfur in the fuel, are principal ingredients in hot gas path corrosion. For this reason, water quality and the prevention of water carry-over are important considerations in the use of evaporative coolers. The prevention of water carry-over was accomplished by correct design of the evaporative cooler and proper installation and operation. Water quality requirements depend on the amount of water carry-over expected (or allowed) and can vary from the use of de-ionized water to water with significant concentrations (as much as several hundred ppm by weight, in water) of sodium and potassium.

The atomic mass of H_2O is less than N_2 and O_2. Due to this the mass of the humid air is less than the mass of the dry air (same volume). Therefore, the humid air has less density than the dry air. As a result of low density air, the amount of dry air mass entering into the gas turbine reduces. Humidity effect on gas turbine performance was studied by Bird and Grabe [5] in which they observed that the moisture in the intake air of a gas turbine can affect its operation and performance in two different ways. One is by possible condensation in the inlet duct and the other one is by changing the gas properties throughout the cycle. They proposed that the condensation can be controlled by restricting engine operation with limits on relative and absolute humidity.

Ondryas *et al*. [6] investigated gas turbine power augmentation in a cogeneration plant using inlet air chilling. The GT inlet air chilling, i.e., air cooling below the ambient wet bulb temperature, can increase the GT capacity needed during peak hours and improve the GT heat rate. They reported that the temperature at the compressor inlet must be above 32 °F to prevent ice buildup on the compressor blades, since the chilled inlet air shall be at 100 percent relative humidity due to moisture condensation during the air chilling process. Due to a major increase in air velocity in the compressor inlet the static temperature of air may drop as much as 10°F. To safeguard against this drop the chilled air temperature should be a minimum of 45°F including a 3°F margin.

El-Hadik [7] studied the impact of atmospheric conditions such as ambient temperature, pressure and relative humidity on gas turbine performance. A fully interactive computer program based on the derived governing equations was developed. The effects of typical variations of atmospheric conditions on power output and efficiency were considered. These include ambient temperature (ranging from −20 to 60°C), altitude (ranging from zero to 2000 m above sea level), and relative humidity (ranging from zero to 100 percent). The thermal efficiency and the specific net work of a gas turbine were calculated at different values of maximum turbine inlet temperature (TIT) and variable environmental conditions.

Kakaras *et al*. [8] studied the compressor intake-air cooling in gas turbine plants. They found that the generated power and the efficiency of gas turbine plants depend highly on the temperature of the inlet air. At high ambient temperatures, a power loss of more than 20%, combined with a significant increase in specific fuel consumption, compared to ISO standard conditions 15°C, could be observed.

As the isentropic efficiency of turbine and compressor increases, the thermal losses are reduced which leads to an increased power output. By reducing the internal component losses of individual component, the overall performance of the gas turbine can be uplifted. This was observed by Petek and Hamilton [9] in their research work. They also proposed some material failure mitigation methods for gas turbine using air, steam or water injection, use of special material such as high performance alloys, use of single-crystal material or use of the thermal barrier coating.

Gord and Dashtebayaz [10] have studied various methods which are commercially available for turbine air inlet cooling aiming to improve the gas turbine efficiency. In their study a new approach had been proposed to improve the performance of a gas turbine. The approach had been applied to one of the Khangiran refinery gas turbines in Iran. The idea was to cool the inlet air of the gas turbine by potential cooling capacity of the refinery natural-gas pressure drop station. The study was part of a comprehensive program aimed to enhance gas turbines performance of the Khangiran gas refinery. The results showed that as the gas turbine inlet air temperature was reduced, the performance of the gas turbine got enhanced.

Ahmadi and Dincer [11] dealt with a comprehensive thermodynamic and exergoeconomic modeling of a gas turbine power plant. In order to validate the thermodynamic model, the results were compared with one of the largest gas turbine power plants in Iran (known as Shahid Salimi gas turbine power plant). Moreover, a multi-objective optimization is performed to find the best design variables. The design parameters considered there were air compressor pressure ratio, compressor isentropic efficiency, gas turbine isentropic efficiency, combustion chamber inlet temperature and gas turbine inlet temperature (TIT). In the multi-objective optimization approach, certain exergetic, economic and environmental parameters were considered through two objective functions, including the gas turbine exergy efficiency and the total cost rate of the system production including cost rate of environmental impact. In addition, fast and effective non-dominated sorting genetic algorithm (NSGA-II) was applied for the optimization purpose. The thermoenviroeconomic objective function was minimized while power plant exergy efficiency was maximized using a developed powerful genetic algorithm. The results of optimal designs were obtained as a set of multiple optimum solutions, called 'the Pareto optimal solutions'. Moreover, the optimized results were compared with the working data from the case study. The results showed that by selecting the optimized data, a 50% reduction in environmental impacts could be obtained. Finally, sensitivity analysis of change in objective functions, when the optimum design parameters vary, was performed and the degree of each parameter on conflicting objective functions had been determined.

Ameri and Enadi [12], in their research paper, did a complete thermodynamic modeling of one of the gas turbine power plants in Iran. They developed a computer program for simulation purposes using Matlab software. The results from the exergy analysis showed that the combustion chamber is the most significant exergy destructor in the power plant, which is due to the chemical reaction and the large temperature difference between the burners and the working fluid. Moreover, the results showed that an increase in the TIT led to an increase in gas turbine exergy efficiency due to a rise in the output power of the turbine and a decrease in the combustion chamber losses. The results revealed that an increase in the TIT of about 350 K can lead to a reduction of about 22% in the cost of exergy destruction.

Popli *et al.* [13] studied the gas turbine efficiency enhancement using waste heat powered absorption chillers in the oil and gas industry. They found that in hot climates, the efficiency of energy-intensive industrial facilities utilizing gas turbines for power generation, such as oil refineries and natural gas processing plants (NGPPs), could be enhanced by reducing gas turbine compressor inlet air temperature. This was typically achieved using either evaporative media coolers or electrically-driven mechanical vapor-compression chillers. However, the performance of evaporative media coolers was constrained in high relative humidity conditions, such as encountered in the Middle East and tropical regions, and such coolers require de-mineralized water supply, while electrically driven mechanical vapor-compression chillers consumed a significant amount of electric power. In their study, the use of gas turbine exhaust gas waste-heat powered, single-effect water lithium bromide (H2O-LiBr) absorption chillers was thermo-economically evaluated for gas turbine compressor inlet air cooling scheme, with particular applicability to Middle East NGPPs. The thermodynamic performance of the proposed scheme, integrated in a NGPP, was compared with that of conventional evaporative coolers and mechanical vapor-compression chillers, in terms of key operating parameters, and either de-mineralized water or electricity consumption, respectively. The results showed that in extreme ambient conditions representative of summer in the Persian Gulf (i.e., 55°C, 80% RH), three steam-fired, single-effect H_2O-LiBr absorption chillers utilizing 17 MW of gas turbine exhaust heat, could provide 12.3 MW of cooling to cool compressor inlet air to 10°C. In the same ambient conditions, evaporative coolers would only provide 2.3 MW cooling capacity, and necessitate consumption of approximately 0.8 kg/s of de-mineralized water to be vaporized. In addition, mechanical vapor-compression chillers would require an additional 2.7 MW of electric energy to provide the same amount of cooling as H_2O-LiBr absorption chillers. The additional electricity generated through gas turbine compressor inlet air cooling using the waste heat powered absorption refrigeration scheme was of approximately 5264 MWh per year, compared to 1774 MWh for evaporative cooling. This study suggested that waste heat absorption refrigeration is an attractive solution to enhance electrical power generation in Middle East NGPPs through gas turbine inlet air cooling, both in terms of thermodynamic and economic feasibility. This strategy would also reduce plant natural gas consumption for power generation, hence production costs and emissions.

Gopinath and Navaneethakrishnan [14] evaluated the performance of a 100 MW capacity gas turbine power plant by using GT PRO software. They studied that the performance of a gas turbine was mainly dependent on the inlet air temperature. The power output of a gas turbine depends on the mass flow rate of air. A reduction of 1°C temperature of inlet air increases the power output by approximately 0.7 MW. To reduce the inlet air temperature, various techniques like evaporative coolers, vapour compression chillers and absorption chillers can be used.

Jasim and Tariq [15] studied the performance of a gas turbine and concluded that it mainly depends on parameters like ambient temperature, compressor pressure ratio and turbine inlet temperature. The most important parameter to increase the life of the turbine blade is the cooling of the blade, which is necessary when a certain temperature of the gas, passing through the blades, is reached. There are various types of cooling models available for cooling a turbine blade. The power output of a gas turbine depends on the mass flow rate through it. This is precisely the reason why on hot days, when air is less dense, power output falls off. They have analyzed the film cooling technique that was developed to cool gases in the initial stages of the turbine blades, where temperature is very high (>1122 K). It was found that the thermal efficiency of a cooled gas turbine was less as compared to the uncooled gas turbine for the same input conditions. The reason is that the temperature at the inlet of the turbine was decreased due to cooling and the work produced by the turbine was slightly decreased. It was also found that the power consumption of the cool inlet air was of considerable concern since it decreased the net power output of gas turbine. In addition, the net power decreased on increasing the overall pressure ratio. Furthermore, the review works revealed that the efficiency of the cooled gas turbine largely depends on the inlet temperature of the turbine and the temperature above 1123 K, required cooling of the blades.

Figure. 2 shows the variation of net work with TIT for different overall pressure ratios. Net work increases on increasing the TIT for a given OPR. Figure. 3 shows the variation of thermal efficiency with TIT for different operating pressure ratio (OPR). It

ISSN: 2350-0557, Volume-4, Issue-3, May-2017
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is clear from the figure that work ratio decreases with the increase of TIT. On the other hand it increases with the increase of OPR.

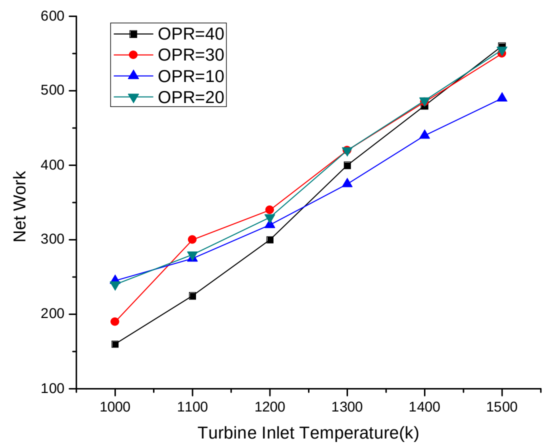

Figure 2. Variation of net work output with turbine inlet temperature Jasim and Tariq [15]

Mohanty and Venkatesh [16] did a performance analysis of a combined cycle gas turbine under varying operating conditions. The combined cycle gas turbine integrates the Brayton cycle as topping cycle and the steam turbine Rankine cycle as bottoming cycle in order to achieve higher thermal efficiency and proper utilization of energy by minimizing the energy loss to a minimum. The effect of various operating parameters such as maximum temperature and pressure of Rankine cycle, turbine inlet temperature and pressure ratio of Brayton cycle on the net output work and thermal efficiency of the combine cycle were investigated. A Matlab simulation had been carried out to study the effects and influences of the above mentioned parameters on the efficiency and work output. It was concluded that for constant pressure ratio and turbine inlet temperature, work output and thermal efficiency were strongly influenced by maximum cycle pressure and maximum temperature of steam turbine cycle. For constant maximum cycle pressure and maximum temperature of steam turbine, the output work was not much affected by pressure ratio, but it was strongly affected by turbine inlet temperature. However, under similar operating conditions, efficiency was significantly affected by both pressure ratio and turbine inlet temperature.

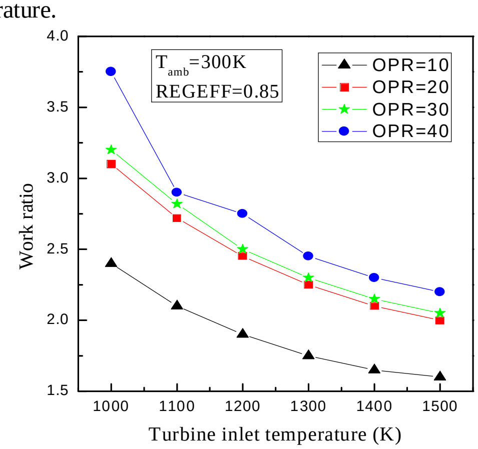

Figure 3. Variation of work ratio with turbine inlet temperature Jasim and Tariq [15]

Ghaderi and Damircheli [17] investigated the factors affecting the efficiency of gas turbine power cycle in their research. The factors affecting the efficiency of the cycle and practical solutions such as increasing the inlet temperature, recovery, internal cooling of the compressor and heat recovery for increasing efficiency were examined. The polytropic efficiency of cycles was evaluated and it showed that the increase in the inlet gas temperature had little effect on turbine efficiency and is limited at high levels of polytropic efficiency. On the other hand, water or steam injection into the gas turbines would not only lead to increased efficiency of the cycle but also increases the flexibility of the turbine. The polytropic efficiency contours of steam turbines was studied and it indicated that rising temperature of exhaust gas from the combustion chamber led to little increase in turbine cycle efficiency and was not considered as an appropriate option in increasing cycle efficiency. Steam injection into turbine not only increased the cycle output power but increased flexibility of gas turbine while working in partial loads. Reducing fluid leakage with optimization of blades design was considered as one of the ways of reducing energy consumption in gas turbines.

Bade and Bandyopadhyay [18] carried out a thermodynamic analysis of gas turbine integrated CHP plant. They reported that the optimal pressure ratio for maximum power plant efficiency is lower than limiting pressure ratio at which specific net work is maximum.

Hosseini et al. [19] investigated a media evaporative cooling system installed in the gas turbine of the Fars (Iran) combined cycle power plant. In their model, different design parameters such as inlet air velocity, geometric shape and sizes and depth of the media had been considered. Analysis of the results showed that at a constant Prandtl number, the cooler effectiveness decreased and pressure drop increased, as incoming air velocity was increased. They concluded that the increase of power output would be more at a lower relative humidity. Based on the data collected for evaluation of the system performance for units 1 and 2 of the power plant at conditions of 3°C and 8% relative humidity, the percentage increase in power output has been 14.6% and 13.3% (11.2 MW and 10.8 MW), respectively. Figure 4 indicates the increase of power output of the power plant with ambient temperature and relative humidity for the installed system

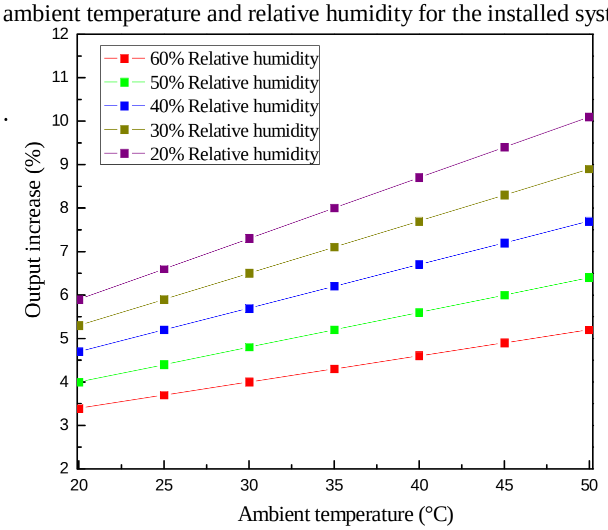

Figure 4. Power augmentation for various ambient temperatures and relative humidity Hosseini et al. [19]

6. SUMMARY

Power generation from coal is not only causing pollution on a global scale but also the resources are limited in nature. The need of gas turbine plants is hence greater than before. Gas turbines have the potential for improved efficiency in power generation, reduced harmful emissions as well as compactness in construction.

This paper includes the important research activities carried out so far, the historical developments and a state-of-the-art assessment of the effect of various operating parameters on the performance of the gas turbine power plant.

From this review work, it is quite evident that ambient conditions have a major impact on the plant's performance. Hence, various techniques have been established so far to enhance the thermal efficiency or power output of a gas turbine power plant by reducing the compressor inlet air temperature. This can be achieved by various intake air cooling methods such as evaporative cooling, fogging or with the help of absorption and mechanical chillers.

By increasing the TIT, the performance of gas turbine power plant can also be augmented. Also, for a constant pressure ratio and turbine inlet temperature, work output and thermal efficiency are strongly influenced by maximum cycle pressure and maximum temperature of steam turbine cycle.

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