PERFORMANCE IMPROVEMENT IN INDUSTRIAL GAS TURBINES

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ABSTRACT
This paper describes the importance of maintaining high efficiency in industrial gas turbines used in power generation to reduce the consumption of non-renewable energy resources and to minimize the harmful effects on our environment. The cost of inefficiency in monetary terms and in the production of harmful emissions is described. The significance of maintaining high component efficiency, especially the prevention of compressor fouling, on the overall engine performance is stressed. The effect of each component performance on engine efficiency is described in some detail. Examples of how component efficiencies can be improved are provided. Recommendations are made for reducing energy consumption by optimized operational procedure and improved engine maintenance.

INTRODUCTION
Industrial gas turbines play a very important role in electrical power generation, in gas and air compression, in the process industry, and in combined cycle and cogeneration applications. The importance of gas turbines will grow in the near future as a result of the imminent economic recovery and the current unpopularity of new nuclear and coal burning power plants. The demand for electricity produced by gas turbines will grow over the next ten years by at least 80 Gigawatts in the United States and by 280 Gigawatts worldwide. Government supported coal gasification projects will open new applications for gas turbines. The energy consumed by gas turbines in the form of natural gas and oil fuels is enormous. This energy is non-recoverable, once burnt it is gone and cannot be reused. This depletion of the earth's store of hydrocarbons deprives future generations of a valuable resource which could be put to better uses than power generation. In addition, burning of hydrocarbons results in undesirable by-products such as CO₂, which may have catastrophic effects on the earth's climate in the future, and pollutants, such as NOₓ, CO, UHC, SOₓ and particulates, which cause acid rain, degradation in our environment and can be detrimental to our health in both the short term and the long run. Therefore, the more hydrocarbons are burned the greater the depletion of a non-renewable natural resource and the greater the production of harmful by-products. The key and the solution to this dilemma of an ever increasing demand for electrical power and the serious concern for our environment is the production of this electricity at the highest possible efficiency. The gas turbine has the potential for power production at the highest possible efficiency, especially when used in combined cycle or cogeneration applications. The challenge is to ensure that these gas turbines are operated at the optimum efficiency over their entire operating life so as to use the least fuel and produce minimum emissions.

IMPORTANCE OF OPTIMUM PERFORMANCE
Modern high firing temperature industrial gas turbines produce electricity at thermal efficiencies of up to 35% in the simple cycle mode and up to 53% in combined cycle operation. This performance level is achieved when the engines are new and clean. Even under favourable operating conditions engine performance deteriorates progressively with increasing operating time (Diakunchak, 1991). The major causes of performance deterioration are compressor and hot end fouling, blade tip and seal rubs, corrosion, erosion, foreign object damage, thermal distortion and engine operation and maintenance practices.

A typical industrial gas turbine in continuous base load operation will run over 8,000 hours per year. Assuming a modern simple cycle 60 MW gas turbine running for one year on natural gas fuel and with an emissions control system that produces 25 PPMVdNOₓ corrected to 15% O₂, the electricity...
produced will be $480 \times 10^6$ KW hours, and fuel burnt will be equivalent to about $5 \times 10^{12}$ KJ. In that one year of operation this gas turbine will produce approximately 230 metric tons of NOX, 92 tons of CO and 12 tons of UHC’s. For each million KW hours of electricity generated, $10 \times 10^6$ KJ of fuel energy is used and 0.5, 0.08, and 0.025 metric tons of NOX, CO and UHC’s respectively are produced. Thus, the lower the operating efficiency of this gas turbine the lower will be the electrical output and the higher will be the fuel consumption and emissions production. For example, if due to compressor fouling and poor maintenance and operating procedures, the output power decreases by 10% and the thermal efficiency by 5%, the fuel consumption will increase by 5% and emissions by 10% per million KW hours of generated electricity. Assuming the cost of electricity to be $0.06/KW hour and that of natural gas to be $2/10^6$ KJ, the yearly cost of the above engine inefficiency will be about $2.3$ million.

The cost of inefficient power generation is high in financial terms. However, the cost of the potential degradation of our environment and the increased hazards to our health and that of future generations may be even more significant. Therefore, ensuring that power is generated at the highest possible efficiency should be a goal that all of us should strive for, be it gas turbine manufacturers, power plant owners or power consumers.

**EFFECT OF COMPONENT PERFORMANCE**

Performance of individual components of a gas turbine engine will have a direct effect on the overall performance of the engine. These components include the inlet system, compressor, combustion system, steam/water injection system, the turbine, the exhaust system, bearings, auxiliaries, gearbox and generator. Each of these components can suffer deterioration in its performance or operate at non-optimum conditions and hence result in degradation of the overall engine performance.

There are many reasons why performance degradation starts on the first day of operation of a new engine and continues with increasing operating time at differing rates depending on environmental conditions, type of fuel, operational procedure and maintenance practices. Even with a good inlet filtration system, when burning clean natural gas fuel and under normal operating conditions, the engine flow path components will become fouled, eroded, corroded, covered with rust scale, distorted and perhaps damaged. The result will be a decrease in the component efficiency and hence in engine performance. Performance deterioration can be classified under the following three headings:

1. Recoverable with cleaning or washing.
2. Non-recoverable with cleaning or washing.
3. Permanent, that is non-recoverable even after complete engine overhaul.

Dust pollen, other particulate materials and oil mists ingested with inlet air flow will block the inlet filters and foul the compressor flow path surfaces. This causes an increase in the inlet system loss and a reduction of compressor inlet flow and efficiency. The particles brought in through the inlet, as well as soot particles produced in the combustor or introduced with injected steam or water, can also accumulate on the turbine and exhaust flow surfaces with detrimental effects. When crude oil is burned in the gas turbine, the hot end is subjected to additional harmful deposits. Depending on the type of fouling, whether it is dry and soft, or sticky, or baked on hard, several procedures can be employed for its removal. The compressor can be cleaned on line using a suitable dry abrasive material or by on line washing using a mixture of water and a detergent. The most efficient method for cleaning the compressor, as well as the hot end components, is to employ off line soak washing with a suitable fluid. The above cleaning methods will restore almost all of the performance loss resulting from fouling of the flow path surfaces. It should be pointed out that icing up of the inlet filter and of the front part of the compressor can have a very serious effect on engine performance, as well as safety, and steps should be taken to prevent it. However, icing is a temporary phenomenon and will not result in permanent performance deterioration, unless it results in compressor damage.

Some surface deposits will remain, even if regular washing is employed, and will detract from engine performance. Flow path erosion, corrosion, distortion and damage, as well as increases in blade tip and seal clearances, will also result in unrecoverable performance deterioration, which will tend to get worse with time.

During a major engine overhaul the critical components are thoroughly cleaned, damaged parts are replaced, airflow recoated and tip and seal clearances restored to their original dimensions, if possible. This procedure will restore the engine almost to its initial condition. However, due to cylinder distortion, increased flow path surface roughness, airflow platform distortion and mismatch, airfoil untwist, increased leakage flow areas, etc., the loss in engine performance will not be completely recovered. Under normal conditions this unrecoverable performance will be small, likely less than 1%. Figure 1 shows typical variation of non-recoverable, with proper cleaning, performance deterioration with increasing operating hours for industrial gas turbines burning different fuels.

In different types of gas turbines, such as heavy duty industrial or aero derivative, single shaft or multi shaft, fixed geometry or variable geometry, mature or latest technology design, etc., the effect of site conditions and operational procedure will have a different effect on component performance and, in turn, the resulting deterioration in engine performance will be different. In all cases, by far the largest contributor to engine performance deterioration is compressor fouling. Operational and maintenance procedures, component distortion, erosion, corrosion, deposits on hot end flow path surfaces and foreign object damage account for the rest of the performance deterioration. Although the information provided in this paper is for a modern, single shaft industrial gas turbine, it can be applied approximately to other types of gas turbines.

Inlet filter fouling, inlet ice buildup, or obstruction in the inlet duct will result in increased inlet system loss and hence in engine performance degradation. For each 25 mm (1 in.) H2O
increase in inlet loss, engine output power will decrease by about 0.4% and its efficiency by about 0.2%, as shown in Figure 2.

All compressors are susceptible to fouling (Saravanamuttoo and Lakshminarasimha, 1985). The rate of fouling and the resulting effects on performance are different for different compressors, depending on their design, coating, etc. Usually about 70 to 85% of engine performance loss is attributed to compressor fouling. More than 10% of output power can be lost in a matter of weeks as a result of fouling. Compressor efficiency reduction due to fouling is about half of the percent loss of inlet air flow. As an example, fouling which decreases the inlet air flow by 5% will cause approximately 2.5% decrease in the compressor efficiency. This will result in 8 to 10% decrease in output power and about 4% decrease in efficiency. In addition to fouling, engine operation results in geometric changes in the compressor and hence in degradation in its performance (Marson, 1992). Frequent and rapid starts will result in cylinder distortion, blade tip and seal rubs, changes in stationary airfoil staggers and in platform misalignment. The effect of blade tip clearance increase on compressor efficiency depends strongly on parameters such as stage loading, surface velocity diffusion, and blade hub/tip ratios (Wilde, 1978). One percent increase in tip clearance area (based on annulus area) will cause approximately one percent decrease in compressor efficiency. This will result in more than one percent drop in output power and in about one percent decrease in engine efficiency. An increase in seal clearances, for a compressor with shrouded stator construction, will cause flow recirculation and detract from compressor performance. One percent increase in leakage area will have a similar effect to that of blade tip clearance increase. Significant changes in airfoil stagger and flow path steps will also have a deleterious effect on compressor performance. Erosion, corrosion and foreign object damage of flow path surfaces will contribute to compressor performance deterioration with increasing operating time. Variable inlet guide vanes, that are not set at the optimum stagger, and improperly closed bleed valves, which are usually used in the engine starting sequence, can adversely affect compressor performance. Since the compressor is one of the key components of a gas turbine engine, it is extremely important to the overall engine performance that...
it operates at its optimum efficiency.

The combustion system is usually not directly responsible for loss in engine performance. Combustion efficiency is not adversely affected even if less desirable fuels are burnt. However, the downstream turbine performance can be affected by soot and hard carbon particles. Changes in combustor outlet temperature profile can result in temporary or even permanent deformation of hot end components. The hot end cylinder warping, blade tip and seal rubs, and increased leakage and cooling flows will result in performance deterioration. Experimental work done on an axial turbine demonstrated that both reduction in airfoil profile thickness caused by surface erosion and increase in airfoil profile thickness caused by deposits on airfoil surfaces result in a significant decrease in turbine performance (Bammert and Stobe, 1970). One percent increase in turbine blade tip clearance will result in 1 to 2% decrease in stage efficiency. The exact amount depends on the stage loading and reaction, aerodynamic loading of the blade tip airfoil section, whether the blade is shrouded or not, etc. Increases in seal leakage and the previously mentioned mechanical changes in the turbine airfoils and flow path surfaces will also detract from turbine performance. Changes occurring in the exhaust will result in diffuser performance loss, which will tend to increase with operating time. This effect can be included in the overall turbine efficiency. A decrease of 1% in the overall turbine efficiency will decrease the engine output power and thermal efficiency by 2.5%. In gas turbines controlled to a specified exhaust temperature the above inefficiency will result in the engine being under fired by 1% of the total variation at different operating conditions. A very important first step in restoring the lost performance is performance monitoring. In order to take the necessary remedial actions the extent of compressor fouling or engine performance deterioration must be detected. Engine performance monitoring can be as simple as measuring, at regular time intervals, the engine output and fuel flow and comparing them to the expected values for the particular operating conditions or consist of a very sophisticated on line health monitoring system. A proper health monitoring system will not only detect a decrease in the engine output power, but also indicate which engine component is responsible for the performance shortfall. To function properly, such a system will require the continuous measurement of most or all of the following parameters: site ambient conditions, output power, auxiliary power, power factor, rotational speed, inlet loss, exhaust loss, water or steam injection rate, instrument bleed air, fuel flow, fuel heating value, inlet guide vane position and temperatures and pressures at critical locations in the engine. In order to have the expected base line values for comparison, the appropriate information must be obtained when the engine is in a "new and clean" condition. The health monitoring system must also incorporate the mathematical model describing the expected engine performance variation at different operating conditions. A very important side benefit of engine performance monitoring is the early detection of potential mechanical problems and their resolution prior to a catastrophic engine failure.

The major portion of gradual performance deterioration with increasing operating time is due to compressor fouling. Compressor fouling, and hence engine performance deterioration, can be monitored by several methods (Diakunchak, 1991). The simplest method is to measure the combustor shell pressure and to compare it to the expected value for a clean engine. Since it is one of the parameters used by the control system to maintain the engine at base load operating point, it is an accurate measurement. With progressive fouling of the compressor flow surfaces, the compressor inlet air flow decreases and as a result the engine matches at a lower pressure ratio. With the engine operating at base load conditions the amount of compressor fouling is directly proportional to the
decrease in the combustor shell pressure compared to the expected pressure for a clean compressor. If the compressor outlet temperature is also measured then, based on the available compressor inlet and outlet conditions, the compressor efficiency can be estimated. The compressor efficiency can then be compared to the expected value for a new and clean compressor. Figures 3 and 4 show the expected base load combustor shell pressure and compressor efficiency variation for an industrial gas turbine.

Another method for determining compressor fouling is based on the measurement of static pressures across the compressor inlet cylinder. The inlet cylinder has a large and continuous reduction in flow area from the inlet flange to the inlet guide vane plane and therefore has a large change in static pressure across it. As for an accelerating nozzle, the ratio of the inlet to outlet static pressure difference divided by the inlet static pressure is independent of the upstream pressure loss for a given volumetric flow. A change in this pressure ratio can result only from flow obstruction within the compressor, and therefore it can be used to detect compressor fouling. The reduction in compressor inlet flow is proportional to the square root of the change in the measured compressor inlet cylinder static pressure ratio compared to that obtained when the compressor was new and clean. Figure 5 shows a typical inlet static pressure ratio curve plotted versus compressor referred speed. If the gas turbine under consideration has been shop tested, then its compressor inlet flow would have been accurately measured. Based on the measured inlet flow and the inlet cylinder static pressure ratio, an inlet scroll calibration curve for the new and clean compressor would have been generated. With the aid of this curve, which is a plot of referred compressor inlet flow versus referred speed, and a shop test generated compressor map, the compressor inlet flow reduction with fouling can be accurately estimated.

### PERFORMANCE IMPROVEMENT

#### General

When performance deterioration has been detected, a decision has to be made on how to regain the performance loss. This can be as simple as replacing a clogged filter, removing inlet ice buildup and washing the compressor, or as complicated as carrying out a major engine overhaul. A major overhaul is usually done after 48,000 hours of engine operation and will require a significant financial investment. But, with the exception of thorough compressor washing, it has the best potential for restoring the engine performance to its initial level. Also, a major overhaul provides the opportunity to introduce changes which will improve engine performance even beyond its new and clean condition.

#### Engine Operation

The operating procedure of a gas turbine will affect engine performance as well as the mechanical integrity of its critical components. Engine starting procedure results in the most severe hot end thermal gradients that the engine experiences during normal operation. At ignition and during engine acel-
operation the combustor exit temperature may exceed, for a short time, that during normal operation. During the starting sequence, hot end cooling is negligible. Therefore, at this time the thermal gradients experienced by the hot end parts are the highest. The resulting high temperatures and thermal shock will lead to distortion, oxidation and corrosion of hot end components and eventually to performance loss. Unless the engine is employed as a peaking unit, the starting sequence should be optimized to prevent the undesirable consequences on engine performance and life. The engine load excursions during normal operation and the engine shutdown sequence should also be optimized. With sophisticated engine health and performance monitoring systems it is possible to operate the engine at its optimum efficiency. This is especially so if the engine is equipped with variable inlet guide vanes and is employed in a combined cycle or in cogeneration applications. In such a case, the engine operation can be specified so as to produce the optimum combination of electrical output power and exhaust heat at any operating condition. Optimizing the gas turbine operating procedure will result in improved engine performance, extend the time between overhauls and improve engine parts life.

### Maintenance

Gas turbine engine maintenance practices have a significant impact on engine performance as well as on the rate of performance deterioration with operating time. One of the key elements in providing safe and efficient engine operation is the control system. It must be properly maintained to ensure that the engine is provided with the correct fuel scheduling during starting and acceleration, that it is operated within the specified safe operating envelope, and that it is not subjected to spurious trips. Optimum engine operation will prevent excessive thermal gradients and hence hardware distortion and blade tip and seal land rubs, and thus enhance engine performance and extend component life. The base load control setting should be checked, to make certain that the engine is operating at the correct firing temperature. Regular inspection of the inlet filter system and compressor washing should be instituted. All oil leaks must be fixed to prevent a fire hazard or oil ingestion into the compressor inlet. Any flange air leaks or cooling air line leaks should be sealed. The fuel system and the water or steam injection systems must be maintained to spurious trips. Optimum engine operation will prevent excessive thermal gradients and hence hardware distortion and blade tip and seal land rubs, and thus enhance engine performance and extend component life. The base load control setting should be checked, to make certain that the engine is operating at the correct firing temperature. Regular inspection of the inlet filter system and compressor washing should be instituted. All oil leaks must be fixed to prevent a fire hazard or oil ingestion into the compressor inlet. Any flange air leaks or cooling air line leaks should be sealed. The fuel system and the water or steam injection systems must be maintained properly to prevent contaminants from getting into the engine. The combustion system equipment should be checked regularly to ensure efficient operation and acceptable radial and circumferential combustor exit temperature gradients. If the engine is run on crude oil fuel, frequent hot end washing should be carried out. The instrumentation monitoring the engine mechanical integrity and performance should be checked frequently and repaired as required. Any unbalance of the rotor system should be corrected to prevent increased vibration and hence blade tip and seal land rubs. Instituting and carrying out proper engine maintenance practices will result in improved engine performance as well as increase the life of the critical engine components.

### Inlet System/Compressor

Blockage of high efficiency inlet filter pads increases with operating time and results in increased inlet loss and in a loss of engine performance. When the inlet loss increases by over 25 mm (1 in.) H2O, the filter pads should be replaced. The self-cleaning pulse filter has a lower loss, but is less efficient in eliminating fine particles from the compressor inlet air. If compressor fouling or inlet ice buildup is a problem, then during a major overhaul, improving the inlet filtration system and incorporation of an inlet air heating system should be seriously considered.

Once compressor fouling has been detected, appropriate action, such as compressor washing, has to be taken. Compressor washing frequency may be determined by economic considerations. On line washing may require operating the engine at part load, while soak washing will require shutting down the engine for a considerable time. Both of these will result in a loss of revenue. On the other hand, if compressor washing is delayed too long, the resulting performance deterioration may cause an even larger economic loss. Therefore, it is very important to detect compressor fouling and to select...
the optimum compressor washing frequency. Usually the
compressor is washed when the mass flow reduction due to
fouling reaches 2 to 3%.

A major engine overhaul is an excellent opportunity to
restore the compressor to its original condition. The compres-
sor flow path surfaces should be thoroughly cleaned, any
damaged or distorted parts removed, any small "nicks"
blended out and any platform mismatch or flow path steps
removed by grinding. Bleed valves should be checked for
tight sealing. Inlet guide vane stagger should be checked and
adjusted if required. Opportunity should also be taken to
restore the stator seal clearances and blade tip clearances.
Seal clearances may be reduced to their as-built values by
installing new seal lands. Restoring blade tip clearances may
be much more difficult, since it will require the installation of
new blades. In compressors which employ the same airfoil
profile of different lengths for several stages, the blades can be
moved one stage downstream and machined to the correct tip
diameter. A new set of blades would still be required for the first
stage in each sequence. Coating the compressor airfoils with
a coating to provide a super smooth surface finish, as well as
increased erosion and corrosion protection, will result in en-
hanced compressor performance. In addition, this type of
coating will tend to reduce the rate of compressor fouling and
will facilitate deposit removal by washing. Following the above
procedure will more than pay for itself by enhanced com-
pressor, and therefore, engine performance.

Combustion System, Turbine, Exhaust System

The combustion system does not affect performance di-
rectly, assuming that it is maintained properly and that it is
supplied with a clean fuel. However, the engine performance
can be improved significantly by increasing the burner outlet
temperature. For each 10°C (18°F) increase in firing tem-
perature the output power will increase by about 2% and
engine thermal efficiency by about 0.4%. In combined cycle
applications there will be an additional performance benefit
due to increased exhaust temperature. In order to allow in-
creased firing temperature, without detracting from engine
mechanical integrity, the cooling of some of the hot end
components will have to be improved. This may be accomplished
by increasing cooling air flow to the critical components. The
increased cooling flow will result in a small penalty in the
performance improvement. The alternative would be to retrofit
the parts, during a major overhaul, with a thermal barrier
coating or with improved cooling design, such as turbine blades
with turbulated radial cooling holes instead of smooth cooling
holes (Stankiewicz and Kirkham, 1991).

The turbine has considerable potential for performance
improvement. Performance deterioration due to deposits on
the hot end flow path surfaces is not as easy to recover as in
the case of the compressor. For engines running on crude oil
fuel, the hot end deposits are removable by water washing.
This is accomplished by injecting water through the existing
atomizing air system when the engine is not running and has
cooled down sufficiently. In this procedure, the rotor is rotated
by the starting device at approximately the ignition rotational
speed. Several injection and then soak cycles are repeated.
This is followed by a spin cycle to dry the engine.

A major engine overhaul provides the opportunity to restore
the turbine performance to its initial level. All the flow path
surfaces can be thoroughly cleaned, any damaged parts
replaced, and small "nicks" and dents blended out. If the airfoil
coating has been damaged, the airfoils should be recoated.
Since blade tip and seal clearances and air and gas leakages
have a very important effect on turbine performance, all clear-
ances should be restored to their original dimensions and any
obvious leakage paths sealed up. If the inter-stage under
the stator seals have suffered severe rubs, they should be re-
placed with new components. Sealing effectiveness can be
improved by installing brush seals, which reduce leakage by a
factor of three or more compared to labyrinth seals (Chupp and
Dowler, 1991). It should be noted that reducing leakage under
the stators will not only improve the turbine performance but will
also reduce hot gas ingestion into the turbine disc cavities and
prevent overheating of disc rims and stator seal holders. Blade
tip clearances can be reduced by weld buildup on blade tips
(Liburdi et al, 1993) or by installing new longer blades. To
reduce the time required for a major overhaul, a spare rotor with
new turbine and compressor blades can be installed. To
prevent large tip clearance increases in the future, an abradable
coating should be applied to the stationary seal plates located
above the blade tips. The function of this coating is to allow
circumferentially localized "machining" of the outer annulus,
which can occur during engine transients, without grinding off
all of the blade tip. The end result is a much tighter average
blade tip clearance. Elimination of any detected leakage paths
may be accomplished by machining faces of mating parts,
which have warped during service, or replacing these parts
with new components. Usually the major part of the non-
recoverable performance deterioration is in the turbine area
and, therefore, every effort should be made during a major
overhaul to restore the turbine as close as possible to its
original condition.

Unless a major failure has occurred, there is usually not
much that can be done to improve exhaust system perform-
ance during a major overhaul. The exhaust should be cleaned,
any debris removed, leaks in the downstream expansion joint
fixed and leakage through the exhaust stack by-pass doors or
louvers reduced or eliminated.

Bearings, Auxiliaries, Gearbox, Generator

It is difficult to detect performance deterioration in com-
ponents included under this heading. During an overhaul
any damaged journal or thrust bearings should be repaired
or replaced. If the original thrust bearing is the flooded type,
then a performance improvement of up to 1% can be
achieved by replacing it with a directionally lubricated type
of thrust bearing. The different engine auxiliaries, the gearbox
and the generator should be inspected and any necessary
refurbishments carried out.
Miscellaneous Performance Improvements

The performance of a gas turbine can be improved above its original level by employing one or more of several currently used methods (Marson, 1993). A substantial increase in engine output power can be achieved by injecting steam or water into the fuel nozzles, or premixing into the fuel, or injecting into the combustor cylinder. For each 1% of injected steam or water (based on compressor inlet flow) the output power will increase by about 4 to 5%. With 1% steam injection the thermal efficiency will increase by about 1.5% and with 1% water injection the thermal efficiency will decrease by about 1%. It should be pointed out that increasing the moisture content of the hot gases flowing through the turbine will increase heat transfer to the turbine vanes and blades. A 1% increase in moisture content will increase the heat input by about 1%. Since the increase in gas-side heat transfer is not offset by a corresponding increase in the internal cooling air heat transfer coefficients, steam or water injection will result in increased metal temperatures of the turbine vanes and blades. The large improvement in gas turbine performance resulting from steam or water injection is due to several factors. Fluid injected into the combustor increases the flow into the downstream turbine as well as the engine match pressure ratio. Energy does not have to be expended in the compressor to compress this additional flow. The addition of steam or water increases the moisture content and hence the specific heat of the gases expanding through the turbine. The combination of the increased turbine mass flow, increased turbine pressure ratio and increased specific heat of the gases flowing through the turbine results in the large performance improvement. However, the cost of demineralizing the injected water and of producing the injected steam has to be taken into consideration. To institute this power augmentation scheme will require some hardware and control system modifications. The amount of fluid injected into the fuel or the combustor will be limited by the combustor flame stability and combustor system component life considerations. The amount of fluid that can be injected into the combustor cylinder will be limited by the allowable compressor surge margin. A side benefit of steam or water injection into a gas turbine for power augmentation is the reduction in NOx emissions.

In locations that experience high ambient temperatures and low relative humidities over most of the year the gas turbine performance can be enhanced by installing an evaporative cooler in the inlet system. As the hot dry inlet air passes through the water spray in the evaporative cooler it loses heat and picks up moisture. The net result is a decreased compressor inlet air temperature and increased humidity. At 30°C (86°F) and 20% Relative Humidity the improvement in output power and thermal efficiency can be as high as 10% and 3% respectively, even accounting for the small increase in inlet loss. Incorporation of an evaporative cooler requires modification of the inlet system, some capital investment and a supply of pure demineralized water.

Incorporation of an inlet air refrigeration system can result in a substantial improvement in engine performance. This system will involve a considerable capital investment. For every 10°C (18°F) reduction in compressor inlet temperature, the engine output power will increase by about 5% and its efficiency by about 2%.

Installation of an inlet supercharger with a downstream and perhaps an upstream evaporative cooler will also enhance the gas turbine performance significantly. However, it will require considerable modification of the inlet system and a very large capital investment. Incorporation of a supercharger will increase engine output power and exhaust flow by about 10% and engine thermal efficiency by about 1%. In combined cycle or cogeneration applications there will be a small performance penalty because of the reduction in the engine exhaust temperature.

RECOMMENDATIONS

1. It is absolutely mandatory to institute performance and health monitoring systems on gas turbines to detect performance deterioration and incipient mechanical problems.
2. If performance deterioration or potential mechanical problems are detected, appropriate action should be taken as soon as possible.
3. Regular compressor, and in some installations turbine, washing should be carried out.
4. The control system must be checked regularly and adjusted, if necessary, to prevent unnecessary thermal shocks and tip and seal rubs during startup and shutdown, and to maintain the engine at the correct base load firing temperature.
5. The gas turbine operating procedure should be optimized to ensure the most efficient operation at all operating conditions.
6. Proper maintenance practices must be instituted to achieve optimum engine performance and increased engine life.

CONCLUSIONS

1. The importance of maintaining the highest possible gas turbine efficiency was underlined.
2. The cost of inefficiency in monetary terms and in the production of harmful emissions was described.
3. The effect of component performance on overall engine performance was described in some detail.
4. Methods of performance deterioration detection were outlined.
5. Concrete suggestions for industrial gas turbine performance improvement were presented.
6. Recommendations were made on how to reduce gas turbine performance deterioration to a minimum and how to restore nearly all of the performance loss resulting from engine operation.
REFERENCES


