Sjournals
Scientific Journals
Scientific Journal of Pure and Applied Sciences (2014) 3(5) 271-279
ISSN 2322-2956
doi: 10.14196/sjpas.v3i5.348

Contents lists available at Sjournals
Scientific Journal of
Pure and Applied Sciences
Journal homepage: www.Sjournals.com

Original article

Investigating factors affecting the efficiency of gas turbine power cycle

R. Ghaderi[a,*], M. Damircheli[b]

[a]*Department of Mechanical Engineering, Faculty of Technical and Engineering, Shahrekord Branch, Islamic Azad University, Shahrekord, IRAN.*
[b]*Department of Mechanical Engineering, Shahre-e-Qods Branch, Islamic Azad University, Tehran, IRAN.*

*Corresponding author; Department of Mechanical Engineering, Faculty of Technical and Engineering, Shahrekord Branch, Islamic Azad University, Shahrekord, IRAN.

A R T I C L E I N F O

Article history,
Received 21 April 2014
Accepted 22 May 2014
Available online 29 May 2014

Keywords,
Gas turbine
Power plant cycle
Efficiency

A B S T R A C T

Today, the use of gas turbines in power generation cycles has been growing. Small size, easy installation, high power-to-mass ratio and the ability to load and unload the cycle quickly are the advantages of such systems. Low efficiency is considered as one of the major disadvantages of such power plants. Thus providing a way to increase cycle efficiency can be very effective in making the cycle more efficient and thus saving fuel consumed in such systems. In this paper the thermal efficiency of the cycle is introduced through describing the mechanism of gas turbine in power generation cycle. Then we will examine the factors affecting the efficiency of the cycle and finally practical solutions such as increasing the inlet temperature, recovery, internal cooling of the compressor and heat recovery for increasing efficiency will be explained. Evaluating the polytropic efficiency of cycles shows that increasing the inlet gas temperature has little effect on turbine efficiency and is limited at high levels of ηpoly. Water or steam injection into the gas turbines will not only lead to increased efficiency of the cycle, but also increases the flexibility of the turbine, too.

© 2014 Sjournals. All rights reserved.

1. Introduction

Long time is not passed since the birth of modern gas turbines compared to other power generation equipment. However, today these devices have to be considered as an important system in producing mechanical power. Gas turbines are one of the simplest and most basic power generator engines. These types of turbines are fixed speed machines which, in combination with axial compressors, can be used for power generation. Despite having advantages such as being small, easy installation, high power-to-mass ratio and the ability to load and unload the cycle quickly, low work efficiency is considered as one of main disadvantages of such equipment. Many theoretical and experimental studies have been conducted in this area, which have led to acceptable results (Wilcock et al. 2005; Dellenback, 2002; Olkhovsky and Trushechkin, 2013; Sahafzadeh and Ataei, 2013; Lebedev and Kostennikov, 2008; Kumar and Singh, 2012). Sahafzadeh and Ataei (2013) proposed a gas turbine which increased the energy efficiency; through ammonia process. Using a combination analysis of pinch and energy, they derived energy dissipation distribution during heat transfer processes and hence identified the suitable areas for gas turbine integration. Through this method, they could succeed in reducing energy dissipation in a practical sample by 19%. Caniere et al. (2006) also could increase cycle efficiency through intercooling of the gas turbine. By simulating the intercooling flow in gas turbine, they concluded that this method not only reduces the work of compression, but also lowers the cooling air temperature. Through simulation, they could define optimum intercooling pressure for achieving maximum gas turbine cycle efficiency.

Power plant cycle simulation results achieved by GTPRO software show that the relative humidity of the incoming air to the cycle has no significant impact on the gas turbine performance, but reducing the inlet air temperature to 10°F increases the turbine efficiency by 2 to 5% (Basha et al. 2011). Schaber and Kolev (2001) offered gas-steam turbine for increasing cycle efficiency. They used a cycle including a gas turbine, a steam turbine and a waste heat utilization were able to achieve thermodynamic efficiency higher than conventional cycle. Through simulation of gas turbine performance, Desa and Al Zubaidy (2011) concluded that by each Kelvin degree increase compared to ISO standard temperature, turbine efficiency will be dropped by 0.1%

By considering the gas turbine position in power generation industry, this paper examines the practical solutions for increasing the efficiency of these turbines. Methods such as recovery, intercooling of the compressor, reheating, water or steam injection and filtration are selected and increasing efficiency of gas turbine cycle is studied by using the methods.

2. Gas turbines work cycle

Gas turbines produce mechanical power by expanding combustion products between the blades. Fig. 1 shows a schematic diagram of gas turbine working cycle. In environmental conditions, air flows in the axial flow compressor from point (1). Incoming air conditions of pressure, temperature and moisture percentage differ among various days and places, but the standard conditions defined by ISO for inlet air is a temperature of 15°C, pressure of 1.013 (bar) and relative humidity of 60%.

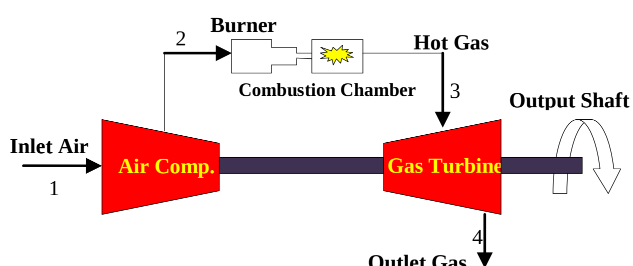

Fig. 1. Schematic diagram of gas turbine work cycle.

Incoming air to the compressor is compressed to higher pressures and the air temperature also increases as a result of compression process. High-pressure and high-temperature air exiting from the compressor enter the combustion chamber at point (2). In this section, the fuel is injected into the air and combustion takes place. Although the gas temperature of the combustion chamber front of this section rises too high, however, the combustion chamber is designed in a way that processes of mixing, combustion, dilution and cooling can be done in it. Thus, when the combustion products leave the combustion chamber and enter the turbine at point (3), the gas temperature will be moderate. Gas turbine absorbs the thermal energy of hot gases and converts it into mechanical work. Energy conversion is performed in two stages: First stage is the turbine nozzle where the gas expands, as a result of which part of the thermal energy is converted into kinetic energy. In the second stage, the gas hits the moving blades and hence, a major portion of this energy is converted into kinetic energy of the blades, as a result of which work is produced. A part of produced work (over 50%) is used to move the compressor and the remaining is utilized in the output flange of gas turbine. Gas turbine cycle can be completed by reducing air volume from points (4) to (1) by decreasing the temperature and transferring heat to the environment. This simple gas turbine cycle is called the Brayton cycle.

3. Gas turbine cycle efficiency

Gas turbine cycle efficiency is measured by comparing output power (mechanical energy at output axis) and the input power. Generally this is efficiency is expressed according to the standard conditions of environment.

Efficiency of a gas turbine, also known as thermal efficiency, is the ratio of work done to the heat supplied, which can be stated as follows:

$$\text{Thermal Heating Efficiency} = 100\text{K}\frac{\text{T}_{\text{max}} - \text{T}_{\text{min}}}{\text{T}_{\text{max}}} \quad (1)$$

where Tmax is the turbine inlet gas temperature, Tmin is the environment temperature and K is the internal loss. Thus, there are three ways to increase efficiency theoretically: Inlet temperature rise, reducing environment temperature and internal losses. In general, the gas turbine cycle efficiency is influenced by the following factors:

-Compressor energy consumption: less energy consumed by the compressor to compress air will lead to increase in turbine output power.

-Temperature of gas exiting from the combustion chamber: The efficiency will increase with increasing this temperature.

-The temperature of exhaust gas: Reduction in exhaust gas temperature leads to increased efficiency.

-Pressure drop in the inlet air filters, exhaust, ducts and chimney: higher pressure drop will result in reduced efficiency.

Efforts done in enhancing the efficiency of gas turbine cycle were mostly based on two main methods: higher turbine inlet gas temperature and making the compressor more efficient. Methods have been developed in this field, among them we can mention the following (Bathie, 1996):

-Using the exhaust gas to heat the exhaust air from the compressor (usable in cold weather conditions)

-Dividing the compressor into two parts and cooling the air between this parts

-Dividing the turbine into two parts and re-heating the gas between these two parts

-Cooling the inlet air (for use in warm climates)

-Reducing the inlet air humidity

-Increasing air pressure in the output section of compressor

-Regular wash and repairing harmed turbine and compressor blades

Of course, all these methods are accompanied by increased costs and some of them lead to decreased output power of the turbine. Thus, a good design is the one which creates a balance between costs, power and output.

Basically, efficiency increase methods can be divided into five main categories:

-Increasing the inlet temperature

-Regeneration

-Compressor internal cooling

-Reheating of the gas turbine

-Water/steam injection

3.1. Increasing the turbine inlet gas temperature

The most common technique for enhancing the efficiency of gas turbine is increasing inlet gas temperature. Turbine efficiency depends on both the inlet and exhaust gas temperature. Higher difference between these two temperatures results in increase of the turbine thermal efficiency. Since the reduction in exhaust gas temperature is limited, raising the temperature of inlet gas is a familiar method in achieving higher efficiencies.

At present, the temperature of gas entering the turbine is higher than melting temperature of some metals used in the turbine. Cooling the first stage of blades has thus become imperative and any additional increase in inlet gas temperature requires better cooling techniques, which can be improved by increasing the flow rate of cooling fluid and enhancing the effect of heat transfer. Obviously, the use of cooling systems leads to gas turbine lower efficiency and it may even lessen the advantage of increasing the inlet temperature. Hence, more accurate examination in this topic is necessary for indicating the effect of increase in the inlet gas temperature along the blade cooling systems.

Fig. 2 shows the contours of cycle efficiency (ηcyc) in the absence of cooling system (Sahafzadeh and Ataei, 2013). The horizontal axis indicates the combustor exhaust gas temperature (Toct) and the vertical axis is indicative of pressure ratio (rp). Contour calculations are performed by assuming standard conditions of input gas (methane fuel in 25°C) and equal polytropic returns of (ηpoly) the turbine and the compressor.

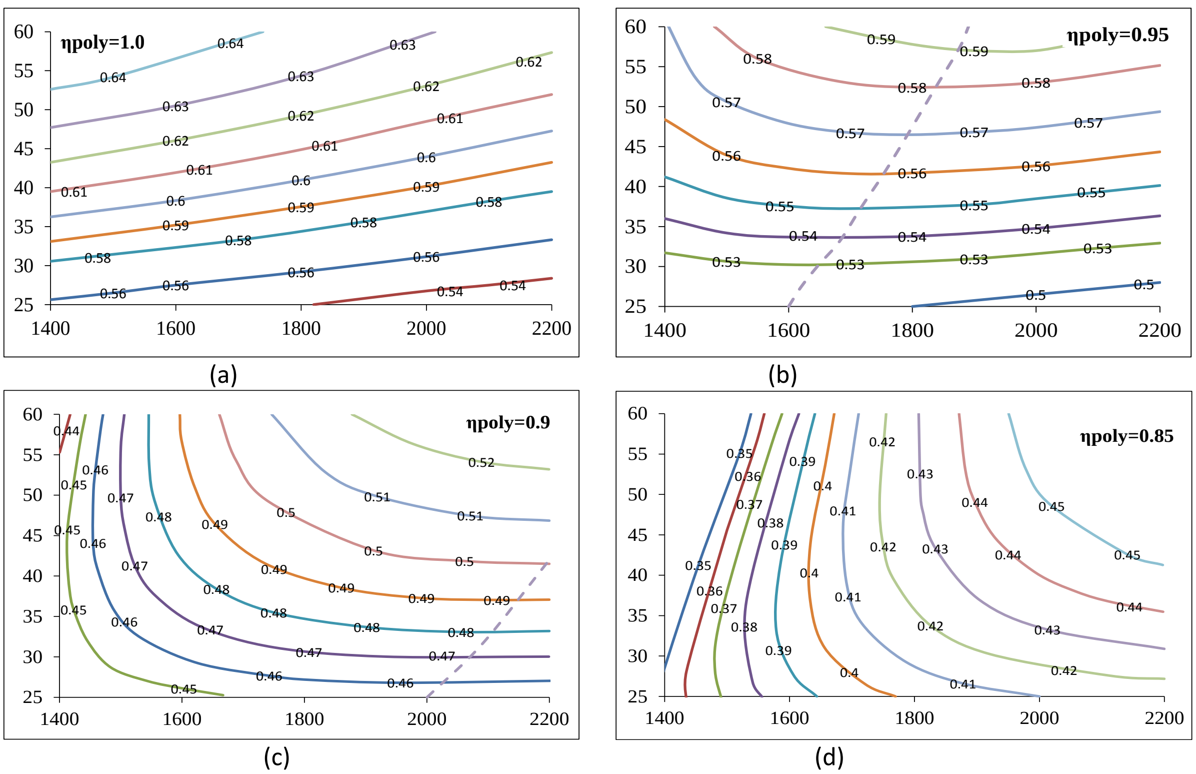

Fig. 2. Contour drawings of gas turbine cycle efficiency in the absence of cooling system (Sahafzadeh and Ataei, 2013).

Fig. 2a shows the status of ηpoly = 1.0 (reversible turbo machine). In this case, ηcyc is only a function of pressure ratio and is independent of the Toct. Hence, the contours are obtained as straight lines. In Fig. 2b the contours are rotated clockwise and are drawn in the lower left. This problem affects ηpoly, so that with increase of Toct in a constant rp, ηcyc will pass its maximum value. The locus of these maximum values is specified with dotted lines in this figure. In the case of ηpoly = 0.9 (Fig. 2c), clockwise rotation of displacement contours is intensified and the locus of the optimal values of Toct is pulled toward higher temperatures. Finally, for ηpoly = 0.85 (Fig. 2d) and for each fixed pressure ratio, ηpoly will rise with the increase of Toct. Thus, by comparing Figs 2a to 2d, it can be concluded that in gas turbines without cooling system, it's only in low ηpoly that efficiency increases by rise in the temperature.

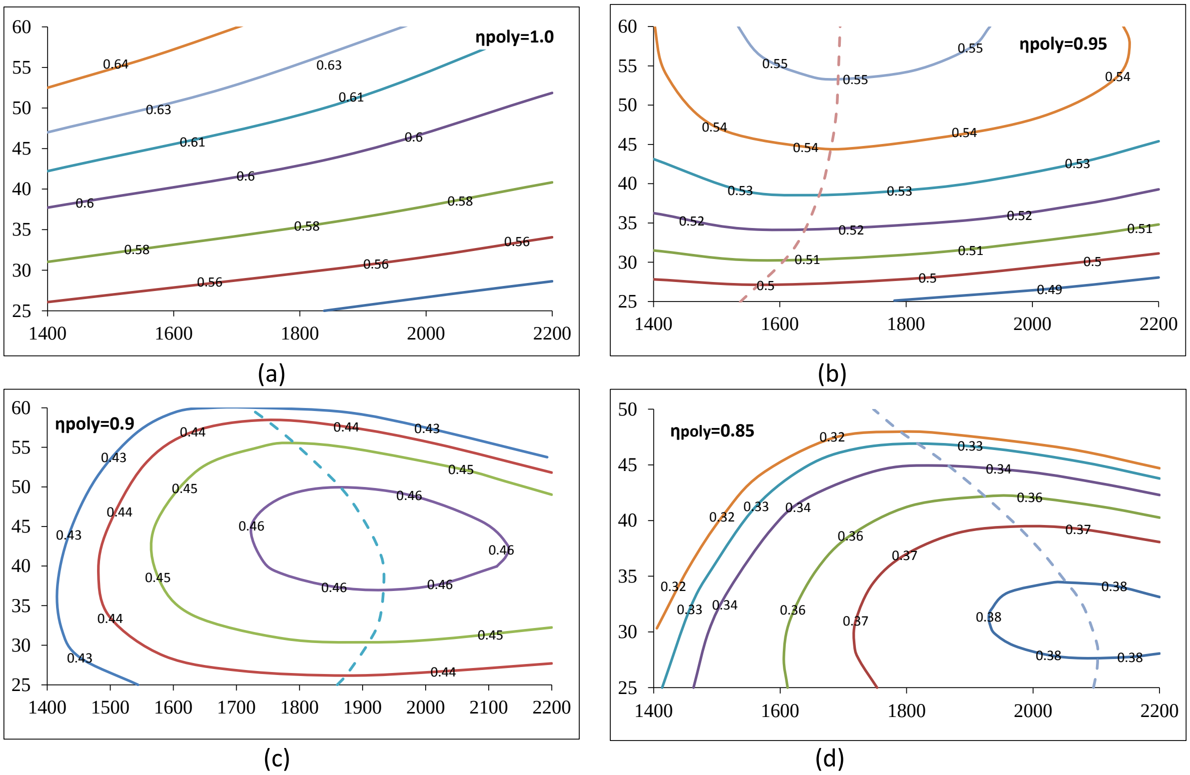

Fig. 3. Contour drawings of gas turbine cycle efficiency in the presence of the cooling system (Sahafzadeh and Ataei, 2013).

3.2. Regeneration

In the gas turbine cycle, the temperature of exhaust gas from turbine is higher than the temperature of which from leaves the compressor (Dellenback, 2002). Thus, by using a heat exchanger, compressed gases can be preheated before entering the combustion chamber and so, save partly on fuel consumption (Fig. 4).

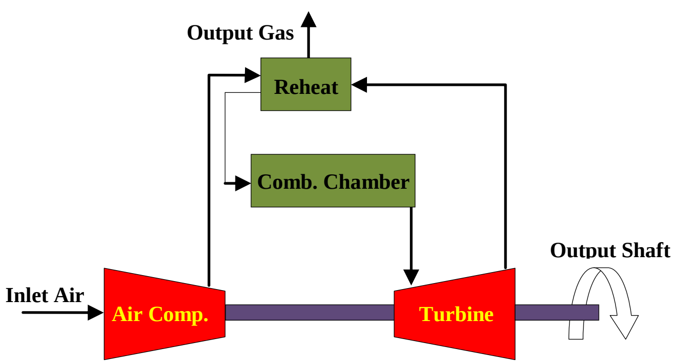

Fig. 4. Schematic diagram of gas turbine cycle with reheat.

Regeneration is performed by installing a heat exchanger in the channel of exhaust gases from the turbine. Although using such recovery is associated with a relatively high cost and decreases the power output, but it will increase the gas turbine cycle efficiency by 5 to 6 percent.

3.3. Intercooling of the compressor

Reducing work needed for compression process is another way to increase the efficiency of gas turbine cycle. In this method, the gas is first compressed to a medium pressure and after passing through an inter cooler, its temperature decreases in a constant pressure process. The cooled gas is returned back into the compressor and this operation is repeated till the exhaust of gas from the compressor (Fig. 5). Intercoolers are heat exchangers which perform heat exchange operation using air or water.

3.4. Turbine reheat

By maintaining the inside temperature of turbine gas in high degrees, the overall efficiency of turbine can be increased. This can be done by continuously heating the gas during expansion operation. But since this is impossible in practical terms, therefore reheating is performed only between the stages (Fig. 6). Reheating increase turbine output power without changing the compressor work or the maximum allowable temperature. Since the reheating deployment leads to increasing turbine exhaust gas temperature, hence using regeneration with reheating system is very effective in making the cycle more efficient.

3.5. Steam/water injection

Steam/water injection not only enhances power cycle, but also increases the flexibility of gas turbine during operation in partial loads and leads to lower emissions of carbon monoxide and unburned hydrocarbons.

Steam injection (saturated or super heat) is done inside the combustion chamber and the water inlet or outlet of the compressor. Water injection at compressor exhaust is accompanied by temperature decrease of the compressed air. This temperature can be minimized with the help of regenerator and since the heat required for the regenerator is supplied from the turbine exhaust gas, thus there is no need to increase the fuel consumption, but it's better to use water injection at compressor inlet, because:

-The pressure of air at the inlet duct is equal to atmospheric pressure .

-Inlet air is isothermal with the environment and there's no need to heat the sprayed water in order to prevent thermal shock.

- Due to the long distance between the compressor and the inlet of air duct, powdered water is completely mixed with the air before reaching the compressor and creates a homogeneous mixture of air and water. Therefore, corrosion and erosion of compressor components in the presence of water droplets is greatly reduced.

In addition to the methods mentioned, efficiency of gas turbines can be increased by other ways, too. Heat recovery, cooling the inlet air, reducing fluid leakage and inlet air filtration are some of them which are discussed in the following sections.

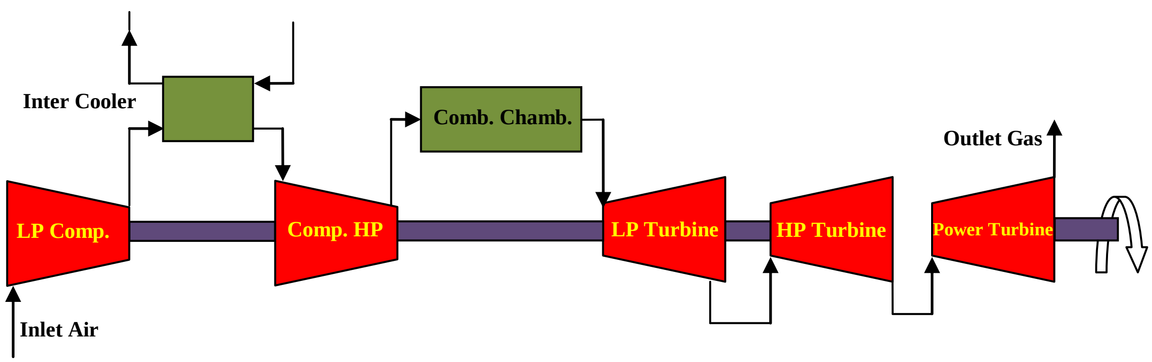

Fig. 5. Schematic diagram of gas turbine cycle with intercooler.

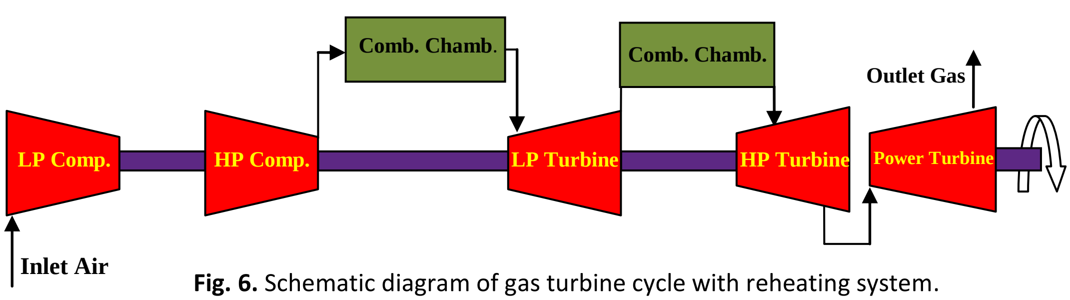

Fig. 6. Schematic diagram of gas turbine cycle with reheating system.

3.6. Heat recovery

Gas turbines produce hot air in high volumes and since a low amount of oxygen of the air entering the combustion chamber is used, the exhaust gas from the turbine has a significant amount of oxygen. Thus, a burner can be placed in the exhaust port of the turbine and so, help the overall thermal energy required by the cycle. This type of burner has high efficiency due to the warm inlet air. Turbine exhaust gas can be used in hot air systems such as furnaces and material dryers, as well as absorption chillers in case of need to high cooling load.

3.7. Cooling of the inlet air

Cooling of inlet air in hot and dry climatic conditions has the best possible effect on raising the turbines cycle efficiency. Since gas turbines work with a fixed volume of air and the power generation depends on the flow rate of fluid, thus the output power of the turbine will decrease by heating the inlet air and lowering its density (Al-lbrahim and Varnham, 2010). Heating of inlet air not only decreases turbine efficiency loss, but also reduces the cycle efficiency by making the compression more difficult.

Selecting a suitable method for cooling of the inlet air depends on the environmental conditions of the gas turbine location. Today, many technologies have been developed that can use for the cooling of the inlet air. Evaporative systems, chillers and combination systems are some of these methods.

3.8. Reduction of leakage flow

The leakage of flow rate causes the energy loss in gas turbines. Leaks generally occur at blades tip, nozzles and areas that need sealing. Internal design of the turbines structure should be in a way that a balance be set between the reduction of the flow leakage and leakage required to prevent the temperature rise (Tony Giampaolo, 2005). The most common way to optimize blades design for achieving such a balance is to use shroud at the tip of the blade. Such shrouds prevent gas leakage through sharp edge sealing as far as possible. Using the frictional materials is also another method to reduce leakage at the tip of the blades. Certainly, less clearance between the tips of the blades and turbine case will lead to the lower fluid leakage.

Reducing clearance will result in increase of blade tip wear on the case. By using wear coating, the occurrence of such phenomena can be prevented as much as possible.

3.9. Inlet air filtration

Small particles generated during turbine operation and chemical impurities in the air and fuel reduce gas turbine efficiency through accumulation, hitting, wear and corrosion (Carter, 2005). Two methods are usually used to solve this problem: better coating of turbine blades and preventing the entry of impurities into the turbine.

Inlet air filtration is very effective in preventing the entry of impurities into the gas turbine, and the selection of appropriate filter can greatly increase the useful life of turbine blades and nozzles. Fig. 7 makes a comparison between the gas turbine blades operating with the same number of hours in two types of filtration. Cleaner blades are mounted in turbine, air filters of which have the ability to absorb five-micrometer particles.

Fig. 7. Comparison of gas turbine blades in two types of filtration (Carter, 2005).

The more efficiency of the filtration will lead to the more pressure drop in the system and increase the efficiency of the gas turbine. Hence, the filtration system design should be in such a way that least efficiency loss in the turbine takes place by maximum reduction in the amount of incoming particles.

Adhesion of the particles to the blades and nozzles will result in their failure. These particles cause the turbulence in the air flow and lead to reduction in flow rate. These failures also affect the outcome by reducing the effective compression ratio.

Particles attached to the blades can be washed away by the fluid spray installed in upstream nozzles of the inflow. Irrigating fluid accompanied by the air flow hits the deposits and removes them from the blades surface through chemical reaction. Washing operation can be performed on during the work or turbine off mode, but washing with the turbine during the work is not as much effective as the off mode and may even lead to abrasion.

4. Conclusion

Today, gas turbines are known as one of the power production generators in the industry. These turbines, having the advantages of being small, high power-to-mass ratio and fast load and unload from the cycle, become more popular in the power generation industry. One of the main major disadvantages is their low efficiency. In this paper, effective factors in the efficiency of gas turbines has been studied and provided practical solutions for increasing cycle of these turbines.

Studying the polytropic efficiency contours of steam turbines indicates that rising temperature of exhaust gas from the combustion chamber leads to little increase in turbine cycle efficiency and is not considered as an appropriate option in increasing cycle efficiency. Steam injection into turbine not only increases the cycle output power but increases flexibility of gas turbine while working in partial loads. Reducing fluid leakage with optimization of blades design is considered as one of the ways of reducing energy consumption in gas turbines.

Proper filtration of the inlet air by reducing the incoming particles increases the useful life of blades and nozzles and leads to stability of the turbine efficiency.

Shortage of production factors forms the basis of economics. At different times, under any condition, a limit

References

Al-lbrahim, A.M., Varnham, A., 2010. A review of inlet air-cooling technologies for enhancing the performance of combustion turbines in Saudi Arabia. Appl. Ther. Eng., Vol. 30 (14-15), pp. 1879-1888.

Basha, M., Shaahid, S.M., Al-Hadhrami, L., 2011. Impact of fuels on performance and efficiency of gas turbine power plants. 2nd Int. Conf. on Adv. Energy. Eng., (ICAEE), Vol. 14, 558-565.

Bathie, W.W., 1996. Fundamentals of Gas Turbines, John Wiley and Sons, New York, 2nd Edition, pp.112-123.

Caniere, H., Willockx, A., Dick, E., DE Paepe, M., 2006. Raising cycle efficiency by intercooling in air-cooled gas turbines. Appl. Ther. Eng., Vol. 26 (16), pp. 1780-1787.

Carter, T.J., 2005. Common failures in gas turbine blades. Eng. Fail. Anal., Vol. 12, pp. 237-247.

Dellenback, P.A., 2002. Improved gas turbine efficiency through alternative regenerator configuration. J. of Eng. for Gas Tur. Power., Vol. 124, pp. 441-446.

De Sa, A., Al Zubaidv, S., 2011. Gas turbine performance at varying ambient temperature. Appl. Ther. Eng., Vol. 31 (14-15), pp. 2735-2739.

Kolev, N., Schaber, K., Kolev, D., 2001. A new type of a gas-steam turbine cycle with increased efficiency. Appl. Ther. Eng., Vol. 21 (4), pp. 391-405.

Kumar, S., Singh, O., 2012. Effect of gas/steam turbine inlet temperatures on combined cycle having air transpiration cooled gas turbine. J. inst. eng., (India): ser. C, Vol. 93(4), pp. 297-305.

Lebedev, A.S., Kostennikov, S.V., 2008. Trends in increasing gas-turbine units efficiency. Ther. Eng., Vol. 55(6), pp. 461-468.

Olkhovsky, G.G., Trushechkin, V.P., 2013. Prospects for increasing the efficiency of gas turbine and steam-gas units. Po. Tech. and Eng., Vol. 47(2), pp. 2-7.

Sahafzadeh, M., Ataei, A., 2013. Integration of a gas turbine with an ammonia process for improving energy efficiency. Appl. Ther. Eng., Vol. 58 (1-2), pp. 594-604.

Tony Giampaolo, P.E., 2002. The gas turbine handbook, Principles and Practices. Fairmont., 2nd Ed., pp. 401-416.

Wilcock, R.C., Young, J.B., Horlock, J.H., 2005. The effect of turbine blade cooling on the cycle efficiency of gas turbine power cycles. J. of Eng. for Gas Tur. and Po., Vol. 127, pp. 109-120.