Efficiency Improvement Methods of Gas Turbine

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Abstract gas turbines are machines that work directly with ambient air, then anything that causes a change in the inlet air condition, effect on turbine efficiency. Relative humidity, Mean sea level and environment temperature have a direct effect on gas turbine efficiency. Generally, peak demand for electricity occurs during the summer time, that the output power of the gas turbine reaches its minimum value for high temperature of inlet air. This makes a lot of pressure on the power industry and to compensate for excess demand, there will always be a need for further investment of new plants. Research done on V94.2 turbines manufactured by Siemens and for pilot studies, thermo flow and GT Pro software was used.

Keywords Gas Turbine, Efficiency, Power Plant

1. Introduction

Turbine power output and efficiency factors include ambient air temperature, relative humidity, Mean sea level, inlet air pressure and fuel type that can decrease outlet power of gas turbine rather than design condition (ISO condition). inlet air temperature and Mean sea level of installation place have most effect on application parameters of turbine that mean sea level cannot be ignored and all outlet power enhancement methods and efficiency improvement Concentrated on inlet air cooling. comparing with new power plant construction costs, apply inlet air cooling methods are less expensive that cause outlet power of gas turbine become closer to nominal power and a significant portion of excess demand will be compensated. in more operating gas turbine, cooling inlet air is under consideration because it is an independence process. this method without any change or modification in main components of gas turbine and considering some technical point is applicable. However Installation location of its equipments is almost independent and separate from main components of gas turbine cycle, all of these cooling inlet air methods are applicable during design, manufacturing or installing. Power enhancement and efficiency improvement of gas methods is

mainly divided into three very general categories were

- a) power enhancement method by inlet air cooling
- b) efficiency improvement and power enhancement methods by using outlet hot gas
- c) saving energy methods

first and second category except using outlet hot gas in absorption chillers for cooling inlet air, all methods need changes in combustion turbine cycle that need turbine design parameters and its thermodynamic conditions. Therefore applying these methods is only possible for companies that access to the turbine design conditions. Considering this restriction, preconditions of power enhancements using inlet air cooling method [1, 2], investigated and determined. it should be taken into by technical-economical criteria and final score to determine optimal method of each power plant, because it can't be expressed by considering only technical advantage of one method or lower cost of another one.

Therefore considering advantages of inlet air cooling methods [3], we technically and economically investigate evaporation, compression refrigeration, absorption refrigeration and fogging method [4, 5, 6] in efficiency improvement of V94.2 gas turbine using thermo flow and GT Pro software. We will briefly explain each of them following:

- a) Water is evaporated in the compressor inlet air duct in evaporation methods. Thus latent heat of water evaporation is taken from air and air is cooled. Reducing the maximum inlet temperature to the dew point or vapor saturation point temperature is fundamental limits and lower primary and operating costs is its benefits of these methods.
- b) In method of compression refrigeration, a radial or impact chiller is used to cooling compressor inlet air by a cooling coil or placing evaporator in air path. Primary cost and especially high operating cost and energy consumption is disadvantages of this method but independent from environmental condition is benefits of this method.
- c) To cool compressor inlet air, an absorption chiller with Liquid refrigerant has been used in absorption refrigeration method. High Primary cost is the problem of this method and lower energy consumption, low operating cost and independence from environmental condition is benefits of

this method.

In high pressure fog spray in inlet air ducts method, water particles are sprayed into the air intake duct. These fine particles of water, by heat absorbing, evaporated and cause cooling the inlet air compressor. On the other hand, the addition of water to the air, which increases flow density, cause power output will increase. It should be mentioned, overspray method for this turbine, by using the software is not recommended. To analyze efficiency improvement method using Thermo flow software, three different methods of evaporation, fog spray and compression and absorption refrigeration (which are divided into four methods) were selected.

Also for better Comparison of efficiency improvement methods and effects of environmental factors on turbine outlet, V94.2 turbine already installed sites, Khorramshahr and Sanandaj is selected. Furthermore, in order to better analyze the results, applied conditions on efficiency improvement systems for both sites is considered as same.

2. Methodology

Figure 1. Cooling system specifications

3.2. Apply Fogging Method [4,5,6]

A 5 degree reduction in temperature and 43 percent increasing humidity system is used to apply fogging method by simulation software. This is shown in figure 2.

For better Comparison of efficiency improvement methods and effects of environmental factors on turbine outlet, V94.2 turbine already installed sites, Khorramshahr and Sanandaj is selected. Furthermore, in order to better analyze the results, applied conditions on efficiency improvement systems for both sites is considered as same that comes in following.

3. Results of Apply Different Method of Efficiency Improvement on Sanandaj Power Plant

3.1. Apply Evaporative Cooling Method [7, 8]

A 5 degree reduction in temperature and 43 percent increasing humidity system is used to apply evaporative cooling method by simulation software. This is shown in figure 1.

Figure 2. fogging system specifications

3.3. Apply Compression Refrigeration Method

A 5 degree reduction in temperature and 43 percent increasing humidity system is used to apply Compression refrigeration method in two case of Air cooled electric chiller and Water cooled electric chiller[9] by simulation software. This is shown in figure 3 and 4.

Flow rate and temperature of inlet and outlet water of system and pumps specification is shown.

Figure 3. Air cooled Compression refrigeration system specification

Figure 4. Air cooled Compression refrigeration system specifications

3.4. Apply Absorption Chiller Method

A 5 degree reduction in temperature and 43 percent increasing humidity system is used to apply absorption chiller method in two case of Single stage water cooled absorption chiller and two stage water cooled absorption chiller by simulation software. This is shown in figure 5 and 6.

Flow rate and temperature of inlet and outlet water of system and pumps specification is shown.

Figure 5. Single stage water cooled absorption chiller

Figure 6. Two stage water cooled absorption chiller

4. Apply Different Method of Efficiency Improvement in Khoramshahr Power Plant.

4.1. Apply Evaporative Cooling Method [7,8]

A 5 degree reduction in temperature and 43 percent increasing humidity system is used to apply evaporative cooling method by simulation software. This is shown in figure 7.

Figure 7. Evaporative cooling system specifications

4.2. Apply Fogging Method

A 5 degree reduction in temperature and 43 percent increasing humidity system is used to apply fogging method by simulation software,. This is shown in figure 8.

Figure 8. fogging system specifications

4.3. Apply Compression Refrigeration Method.

A 5 degree reduction in temperature and 43 percent increasing humidity system is used to apply Compression refrigeration method in two case of Air cooled electric chiller and Water cooled electric chiller by simulation software. This is shown in figure 9 and 10. Flow rate and temperature of inlet and outlet water of system and pumps specification is shown.

Figure 9. Air cooled Compression refrigeration system specification

Figure 10. water cooled Compression refrigeration system specifications

4.4. Apply Absorption Chiller Method

A 5 degree reduction in temperature and 43 percent increasing humidity system is used to apply absorption chiller method in two case of Single stage water cooled absorption chiller and two stage water cooled absorption chiller by simulation software. This is shown in figure 11 and 12.

Flow rate and temperature of inlet and outlet water of system and pumps specification is shown.

Figure 11. Single stage water cooled absorption chiller

Figure 12. Two stage water cooled absorption chiller

5. Different Method of Efficiency Improvement Analysis on Pilot Turbine Using Thermo Flow and GT Pro Software and Exploit Heat Balance of Each Method.

Version 19 of Thermo flow software, produced in 2009 has been used to analyzing efficiency improvement methods. As mentioned before, to analyze efficiency improvement method using Thermo flow software, three different methods of evaporation, fog spray and compression and absorption refrigeration (which are divided into four methods) were selected. Also for better Comparison of methods for improving the efficiency and effects of environmental factors on turbine outlet, two V94.2 turbine already installed sites is selected. In the following, we present and analyze methods. Furthermore, in order to better analyze the results, applied conditions on efficiency improvement systems for both sites is considered as same.

5.1 Basic Case

Considering environmental condition of Sanadaj power plant, simulation is performed by simulation software [7, 10, 11]. This is shown in figure 13. Also result of simulation and heat balance is presented in table 1.

Figure 13. software output of Sanadaj power plant in basic case

Table 1. software output of Sanadaj power plant in evaporative cooling method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10486	34.33	134.9	Basic case

5.2. Using Evaporative Cooling

In next step, evaporative cooling is used and simulated by simulation software. This is shown in figure 14. Also result of simulation and heat balance is presented in table 2.

Figure 14. software output of Sanadaj power plant in evaporative cooling method**Table 2.** software output of Sanadaj power plant in evaporative cooling method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10410	34.58	139.9	evaporative cooling method

In this case, compressor inlet temperature is 9.69 C, relative humidity is 89.74% and Flow rate of inlet air is 435.8 kg. that rather than basic case with power of 134.9 W, efficiency 34.33%, compressor inlet temperature 15C, relative humidity 43.3% and inlet air Flow rate 426.8 kg this result is produced, Increasing in power 5 MW, efficiency 0.25%, relative humidity 43.3% and inlet air Flow rate 9 kg and reducing in compressor inlet temperature 5.31 C.

5.3. Using Fogging Method

In next step, fogging method is used and simulated by simulation software. This is shown in figure 15. Also result of simulation and heat balance is presented in table 3.

Figure 15. software output of Sanadaj power plant by fogging method

Table 3. software output of Sanadaj power plant in fogging method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10410	34.58	139.9	fogging method

In this case, compressor inlet temperature is 9.69 C, relative humidity is 89.74% and Flow rate of inlet air is 435.8 kg. that rather than basic case with power of 134.9 W, efficiency 34.33%, compressor inlet temperature 15C, relative humidity 43.3% and inlet air Flow rate 426.8 kg this result is produced, Increasing in power 5 MW, efficiency 0.25%, relative humidity 43.3% and inlet air Flow rate 9 kg and reducing in compressor inlet temperature 5.31 C.

5.4. Using Compression Refrigeration Method

In next step, Compression refrigeration method in two case of Air cooled electric chiller and Water cooled electric chiller is used and simulated by simulation software. This is shown in figure 16 and 17. Also result of simulation and heat balance is presented in table 4 and 5.

Figure 16. software output of Sanadaj power plant by Air cooled Compression refrigeration method

Figure 17. software output of Sanadaj power plant by air cooled Compression refrigeration method

Table 4. software output of Sanadaj power plant by air cooled Compression refrigeration method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10420	34.55	139.1	air cooled Compression refrigeration method

Table 5. software output of Sanadaj power plant by two stage water cooled absorption chiller method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10420	34.55	139.1	two stage water cooled absorption chiller method

In this case, compressor inlet temperature is 9.69 C, relative humidity is 89.74 and Flow rate of inlet air is 435.8 kg. that rather than basic case with power of 134.9 W, efficiency 34.33%, compressor inlet temperature 15C, relative humidity 43.3% and inlet air Flow rate 426.8 kg this result is produced. Increasing in power 5 MW, efficiency 0.25%, relative humidity 43.3% and inlet air Flow rate 9 kg and reducing in compressor inlet temperature 5.31 C.

In this case, compressor inlet temperature is 10 C, relative humidity is 64.32% and Flow rate of inlet air is 434.5 kg. that rather than basic case with power of 134.9 W, efficiency 34.33%, compressor inlet temperature 15C, relative humidity 43.3% and inlet air Flow rate 426.8 kg this result is produced, Increasing in power 4.2 MW, efficiency 0.22%, relative humidity 17.88% and no change in inlet air Flow rate and reducing in compressor inlet temperature 5 C.

5.6. Using Absorption Chiller Method

In next step, absorption chiller method in two case of Single stage water cooled absorption chiller and two stage water cooled absorption chiller is used and simulated by simulation software. This is shown in figure 18. Also result of simulation and heat balance is presented in table 6.

Figure 18. software output of Sanadaj power plant by two stage water cooled absorption chiller method

Table 6. software output of Sanadaj power plant by two stage water cooled absorption chiller method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10420	34.55	139.1	single stage water cooled absorption chiller method

In this case, compressor inlet temperature is 8 C, relative humidity is 73.64% and Flow rate of inlet air is 438.1 kg. that rather than basic case with power of 134.9 W, efficiency 34.33%, compressor inlet temperature 15C, relative humidity 43.3% and inlet air Flow rate 426.8 kg, this result is produced, Increasing in power 4.2 MW, efficiency 0.22%, relative humidity 17.88% and no change in inlet air Flow rate and reducing in compressor inlet temperature 5 C.

6. Different Method of Efficiency Improvement Analysis in Khoramshahr Power Plant

It should be mentioned, complete result of software and heat balance presented in appendix 3

6.1. Basic Case

At first, considering environmental condition of Sanadaj power plant, simulation is performed by simulation software. This is shown in figure 19. Also result of simulation and heat balance is presented in table 7.

Figure 19. software output of khoramshahr power plant in basic case

Table 7. software output of Khoramshahr power plant in evaporative cooling method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10652	33.8	152.3	Basic case

In this case, compressor inlet temperature is 26.3 C, relative humidity is 50.5% and Flow rate of inlet air is 495.1 kg

6.2. Using evaporative cooling

In next step, evaporative cooling is used and simulated by simulation software. This is shown in figure 20. Also result of simulation and heat balance is presented in table 8.

Figure 20. software output of khoramshahr power plant in evaporative cooling method

Table 8. software output of Khoramshahr power plant in evaporative cooling method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10571	34.1	157.4	Evaporative cooling method

In this case, compressor inlet temperature is 21.1 C, relative humidity is 82.9% and Flow rate of inlet air is 503.3 kg. that rather than basic case with power of 152.3 W, efficiency 33.8%, compressor inlet temperature 26.3C, relative humidity 50.5% and inlet air Flow rate 495.1 kg this result is produced, Increasing in power 5.1 MW, efficiency 0.3%, relative humidity 32.4% and inlet air Flow rate 8.2 kg and reducing in compressor inlet temperature 5.2 C.

6.3. Using Fogging method

In next step, fogging method is used and simulated by simulation software. This is shown in figure 21. Also result of simulation and heat balance is presented in table 9.

Figure 21. software output of Khoramshahr power plant by fogging method**Table 9.** software output of Khoramshahr power plant in fogging method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10571	34.1	157.4	Fogging method

In this case, compressor inlet temperature is 21.1 C, relative humidity is 82.9% and Flow rate of inlet air is 503.3 kg. that rather than basic case with power of 152.3 W, efficiency 33.8%, compressor inlet temperature 26.3C, relative humidity 50.5% and inlet air Flow rate 495.1 kg this result is produced, Increasing in power 5.1 MW, efficiency 0.3%, relative humidity 32.4% and inlet air Flow rate 8.2 kg and reducing in compressor inlet temperature 5.2 C.

6.4. Using Compression Refrigeration Method

In next step, Compression refrigeration method in two case of Air cooled electric chiller and Water cooled electric chiller is used and simulated by simulation software. This is shown in figure 22. Also result of simulation and heat balance is presented in table 10.

Table 10. software output of Khoramshahr power plant by air cooled Compression refrigeration method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10579	34.03	156.6	Air cooled Compression refrigeration method

In this case compressor inlet temperature is 21.3 C, relative humidity is 68.07% and Flow rate of inlet air is 502.3 kg. that rather than basic case with power of 152.3 W, efficiency 33.8%, compressor inlet temperature 26.3C, relative humidity 50.5% and inlet air Flow rate 495.1 kg this result is produced. Increasing in power 4.3 MW, efficiency 0.23%, relative humidity 17.57% and inlet air Flow rate 7.2 kg and reducing in compressor inlet temperature 5 C.

6.5. Using Absorption Chiller Method

In next step, absorption chiller method in two case of Single stage water cooled absorption chiller and two stage water cooled absorption chiller is used and simulated by simulation software. This is shown in figure 23 and 24. Also result of simulation and heat balance is presented in table 11 and 12.

Figure 22. software output of Khoramshahr power plant by Air cooled Compression refrigeration method

Figure 23. software output of Khoramshahr power plant by single stage water cooled absorption chiller method

Figure 24. software output of Khoramshahr power plant by two stage water cooled absorption chiller method

Table 11. software output of Khoramshahr power plant by single stage water cooled absorption chiller method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10579	34.03	156.6	Single stage water cooled absorption chiller method

Table 12. software output of Khoramshahr power plant by two stage water cooled absorption chiller method

Heat Rate(kJ/kWh)	Efficiency	Power (MW)	
10579	34.03	156.6	Two stage water cooled absorption chiller method

In this case compressor inlet temperature is 21.3 C, relative humidity is 68.07% and Flow rate of inlet air is 502.3 kg. that rather than basic case with power of 152.3 W, efficiency 33.8%, compressor inlet temperature 26.3C, relative humidity 50.5% and inlet air Flow rate 495.1 kg this result is produced. Increasing in power 4.3 MW, efficiency 0.23%, relative humidity 17.57% and inlet air Flow rate 7.2 kg and reducing in compressor inlet temperature 5 C.

7. Discussion and Conclusion

Software result of Sanandaj power plant summarized in table 13

Table 13. Result of different efficiency method improvement in Sanadaj power plant

Efficiency	Power (MW)	
34.33	134.9	Basic case
34.58	139.9	Fogging method
34.58	139.9	Evaporative Cooling method
34.55	139.1	Air cooled Compression refrigeration method
34.55	139.1	Water cooled Compression refrigeration method
34.55	139.1	Single stage water cooled absorption chiller method
34.55	139.1	Two stage water cooled absorption chiller method

Chart 1. Increasing power of different systems in Sanandaj power plant.

According to table 13 and chart 1 it is observed that, using fogging and evaporative methods are most effective methods of efficiency improvement in Sanandaj power plant, that cause about 5MW increasing in efficiency. After that, compression refrigeration and absorption refrigeration methods with efficiency increasing about 4MW are in second place. However, at this stage, the economic evaluation methods not mentioned and the classification is done solely in terms of efficiency improvement.

Software result of Khoramshahr power plant summarized in table 14.

Table 14. Result of different efficiency method improvement in Khoramshahr power plant

Efficiency	Power (MW)	
33.8	152.3	Basic case
34.1	157.4	Fogging method
34.1	157.4	Evaporative Cooling method
34.03	156.6	Air cooled Compression refrigeration method
34.03	156.6	Water cooled Compression refrigeration method
34.03	156.6	Single stage water cooled absorption chiller method
34.03	156.6	Two stage water cooled absorption chiller method

Chart 2. Increasing power of different systems in Khoramshahr power plant.

According to table 14 and chart 2 it is observed that, using fogging and evaporative methods are most effective methods of efficiency improvement in Khoramshahr power plant, that cause about 6MW increasing in efficiency. After that, compression refrigeration and absorption refrigeration methods with efficiency increasing about 4MW are in second place. However, at this stage, the economic evaluation methods not mentioned and the classification is done solely in terms of efficiency improvement.

7.1. Technical and economical analysis of different efficiency improvement methods in Sanandaj power plant [12,13]

Calculation result of Sanandaj power plant construction and efficiency improvement systems installation, presented in table 15

Table 15. Calculation result of Sanandaj power plant construction and efficiency improvement systems installation

Each KW cost (\$)	Efficiency	Power (MW)	
594	34.33	134.9	Basic case
590	34.58	139.9	Fogging method
592	34.58	139.9	Evaporative Cooling method
598	34.55	139.1	Air cooled Compression refrigeration method
600	34.55	139.1	Water cooled Compression refrigeration method
597	34.55	139.1	Single stage water cooled absorption chiller method
599	34.55	139.1	Two stage water cooled absorption chiller method

Chart. 3 power increasing and economical results of different efficiency improvement methods in Sanandaj power plant

According to Table 15 and chart 3 it is observed that, fogging method is most appropriate method in term of increasing power and construction coast per KW, and next, evaporative cooling method is recommended.

After all it can be resulted, by using fogging method, outlet power of turbine is increased about 5 MW, however construction cost per KW reduced 4\$.

7.2. Technical and Economical Analysis of Different Efficiency Improvement Methods in Khoramshahr Power Plant

Calculation result of Khoramshahr power plant construction and efficiency improvement systems installation, presented in table 16

Table 16. Calculation result of Khoramshahr power plant construction and efficiency improvement systems installation

Each KW cost (\$)	Efficiency	Power (MW)	
528	33.8	152.3	Basic case
527	34.1	157.4	Fogging method
528	34.1	157.4	Evaporative Cooling method
534	34.03	156.6	Air cooled Compression refrigeration method
534	34.03	156.6	Water cooled Compression refrigeration method
534	34.03	156.6	Single stage water cooled absorption chiller method
532	34.03	156.6	Two stage water cooled absorption chiller method

Chart 4. power increasing and economical results of different efficiency improvement methods in Khoramshahr power plant

According to Table 16 and chart 4 it is observed that, fogging method is most appropriate method in term of increasing power and construction coast per KW, and next, evaporative cooling method is recommended.

After all it can be resulted, by using fogging method, outlet power of turbine is increased about 6 MW, however construction cost per KW reduced 4\$.

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