Open Access Journal

Journal of Power Technologies 92 (4) (2012) 249–257

journal homepage:papers.itc.pw.edu.pl

Impact of inlet air cooling on gas turbine performance

Ewa Pyzik, Szymon Jarzębowski *, Andrzej Miller

Warsaw University of Technology, Institute of Heat Engineering
21/25 Nowowiejska Street, 00-665 Warsaw, Poland

Abstract

This article presents different options for gas turbine inlet air cooling. The method of defining power gain caused by air cooling, as well as the results of applying air cooling to several different gas turbines and one gas turbine in combined cycle in domestic ambient conditions are presented and discussed. Significant turbine power gains were obtained.

Keywords: Gas turbine, chillers, inlet air cooling

1. Introduction

Gas turbines working in open cycle are engines which are sensitive to ambient temperature changes. The increase in inlet air temperature, especially pronounced in summer, causes a significant decrease in gas turbine output power. The reduction of inlet air temperature can be achieved by the application of air cooling through water atomization or installing a chiller in the inlet ducting. The use of a cooler or chiller is economically justified if the profits from the increase in power exceed the related capital and operating costs and the climate conditions for effective operation are met.

2. Evaporative cooling

Evaporative cooling, achieved by evaporation of water injected into the inlet duct, is a cost-effective way of recovering turbine capacity during high temperature and low or moderate humidity periods. This method is hindered by ambient temperatures of 10–15°C and above. In lower temperatures there is a higher risk of ice formation on the compressor's inlet guide vanes. The effectiveness of cooling is determined by the ratio of the reduction in the temperature in the cooler to the largest possible reduction, when the wet bulb temperature is achieved. The actual drop in temperature depends on the device's construction and the atmospheric conditions.

The best evaporating cooling effects occur in dry and hot climates. Cooling is achieved through atomizing water inside the inlet duct. This type of cooler is composed of nozzles placed across the face of gas turbine inlet and upstream coalescer. These nozzles distribute a fine mist into the inlet air stream, and non-evaporated water carry over is eliminated in the coalescer. Nozzles can be installed both upstream and downstream air filters. However, because of the greater risk of impurities caused by the large number of small size nozzles placed immediately upstream of the gas turbine compressor inlet, it is recommended that this system in only installed upstream air filters.

*Corresponding author

Email addresses: ewa.i.pyzik@gmail.com (Ewa Pyzik), jarzebowski.szymon@gmail.com (Szymon Jarzębowski *), andrzej.miller@itc.pw.edu.pl (Andrzej Miller)

An additional advantage of this type of equipment is enhanced pre-filtration, which extends the life span of the main filters.

According to Jonsson and Yan [1] an evaporative cooler can increase the relative humidity of the inlet air to about 90%, thus increasing the gas turbine power output by 5–10% and efficiency by 1.5–2.5%.

3. Cooling by chillers

Chillers, unlike evaporative coolers, are not limited by the wet bulb temperature. The possible power gain is restrained by the turbine and the capacity of the chilling device to produce coolant and heat exchange limits between coils and air. Primarily the cooling proceeds according to the line of the constant humidity ratio. When saturation point is achieved the water contained in the air starts to condense. Further heat exchange cools the condensate and air, causing even more intense condensation. Due to the relatively high heat of vaporization of water, most of the cooling provided is consumed by the condensation, and only a little part by the further temperature reduction. Therefore, when the cooled temperature reaches dew point, the effectiveness of the cooling decreases. Thus chillers should be designed in a way that avoids excessive condensation, because this can be a factor in high energy consumption.

Jonsson and Yan [1] concluded that chillers can increase gas turbine power output by 15–20% and efficiency by 1–2% (i.e. if gas turbine exhaust gas energy is recovered). However, the specific investment cost of chillers is higher than for evaporative coolers.

4. Alternative solutions

Apart from evaporative coolers and chillers, other air cooling methods, such as the storing of cold, are considered. The aim of this process is to gain similar benefits to those obtained when chillers are used, while eliminating the large energy consumption for the cooling system's own needs during peak hours. A system of this type allows almost full turbine power output independence from ambient conditions. The rationality of choosing cooling system with storing of cold is dictated only by the economics of the investment costs involved. Although in the case presented in [2], when the amount of required power augmentation during peak hours could only be met by using this system, even the costs of it became only a minor criterion.

Farzaneh-Gord and Deymi-Dashtebayaz [3] have proposed another system for output power enhancement. In their method, natural gas supplied to a power plant in a high pressure pipeline passes through the turbo-expander. Its temperature drops and considerable cooling capacity is created, which can be used for inlet air cooling. In addition, the power gained from the turbo-expander increases the total power output. Such solution can be considered only in cases when gas is delivered to the power plant at high pressure.

5. Local ambient conditions and choice of cooling method

EU Directive 2009/28/EC [4] requires Poland to increase the share of renewable sources in power generation and to reduce CO_2 emissions. These goals make it more profitable to use gas turbines for power generation. Owing to the short timeframe required for gaining nominal power, gas turbines work well as balancing devices in a power system containing renewable energy sources, which are dependent on factors which are difficult to control. Also, the higher cost of CO_2 emission allowances related to power generated by coal-fired power plants mitigates the high price of the fuel for gas turbines, which was formerly one of the main reasons for its lack of profitability.

A review of power demand during the summer period over the last four years shows a growth trend. Based on this information, it can be assumed that soon the gap between energy consumption in summer and winter will close. Accordingly, the use of gas turbine inlet air cooling during the summer season is worth considering.

Farzaneh-Gord and Deymi-Dashtebayaz in [5] presented a comparison between two standard cooling methods and one with turbo-expander inlet air cooling to improve the performance of a refinery gas turbines in Khangiran, north-east Iran, where the climate is hot and dry. The two standard air cooling methods used either an evaporative cooling system or a mechanical chiller. The results indicated that in such ambient conditions, the use of chillers causes the largest increase of efficiency, while the evaporative cooling system causes the smallest increase. However, as the turbo-expander method has the shortest payback period, this solution seems to be the most advantageous.

Considering the pressure of gas supplying Polish power plants, the application of an inlet air cooling system based on a turbo-expander is impossible, because usually there is no pressure reduction point to be replaced by a turbo-expander.

As currently, the largest power demand in Poland occurs during winter, the Polish power system has a power reserve during peak hours in summer and energy prices are not dramatically high then. Therefore, the installation of an expensive system for the storage of cold, which aims to maximize the capacity of energy production in the summer peak hours, is economically inefficient. Even if energy demand in winter and summer become equal, prices will not be sufficiently high to justify the costs of investment, because the power reserve from coal-fired power plants will still be large enough.

Taking these disadvantages into account only two methods of inlet air cooling, which are efficient in Polish conditions, are discussed further: evaporative cooling and cooling by chillers.

6. Method of calculation

The Polish summer has a temperature range of 15°C to 30°C and variable humidity. The following simulations were conducted in these climatic conditions for four different simple cycle gas turbines and one in combined cycle. The lowest temperature of cooled air was set at 5°C, because of the hazard of icing on the compressor's inlet guide vanes. For the purpose of calculating the gained power increase in case of cooling by chillers, a coefficient of performance COP was set at the value of 4.21, and in the case of evaporative cooling, the power consumed for water injection of 1 kg/s (NP) was set at the value of 10 kW (based on an analysis of data shared by producers [6]). As an additional assumption, for evaporative cooling the minimum cooled air temperature was set at 0.5°C higher than the wet bulb temperature.

In order to calculate the gas turbine power increase by using inlet air cooling, the following schemes were used:

Sequence of actions for evaporative cooling is shown in Fig. 1, where:

- t_0 is ambient temperature
- f_0 is ambient relative humidity
- x_0 is ambient specific humidity
- t_w is wet bulb temperature
- t_1 is temperature of cooled air
- x_1 is specific humidity of cooled air
- f_1 is cooled air relative humidity set at 1.0
- m is mass of water injected during cooling for 1 kg of air
- N is output power
- G is inlet air flow
- ΔN is gas turbine power increase
- $\overline{\Delta N}$ is relative power increase

Sequence of actions in case of using chillers is shown in Fig. 1, where:

- t_0 is ambient temperature
- f_0 is ambient relative humidity
- x_0 is ambient specific humidity
- t_{1i} is cooled air temperature for 'i' step
- Δt is change of temperature for one step
- x_{1i} is specific humidity of cooled air for 'i' step
- f_{1i} is cooled air relative humidity for 'i' step set at 1.0
- $\Delta h_{1i}\,(t_0,\ t_{1i},\ x_0,\ x_{1i})$ is change of enthalpy of humid air for 'i' step

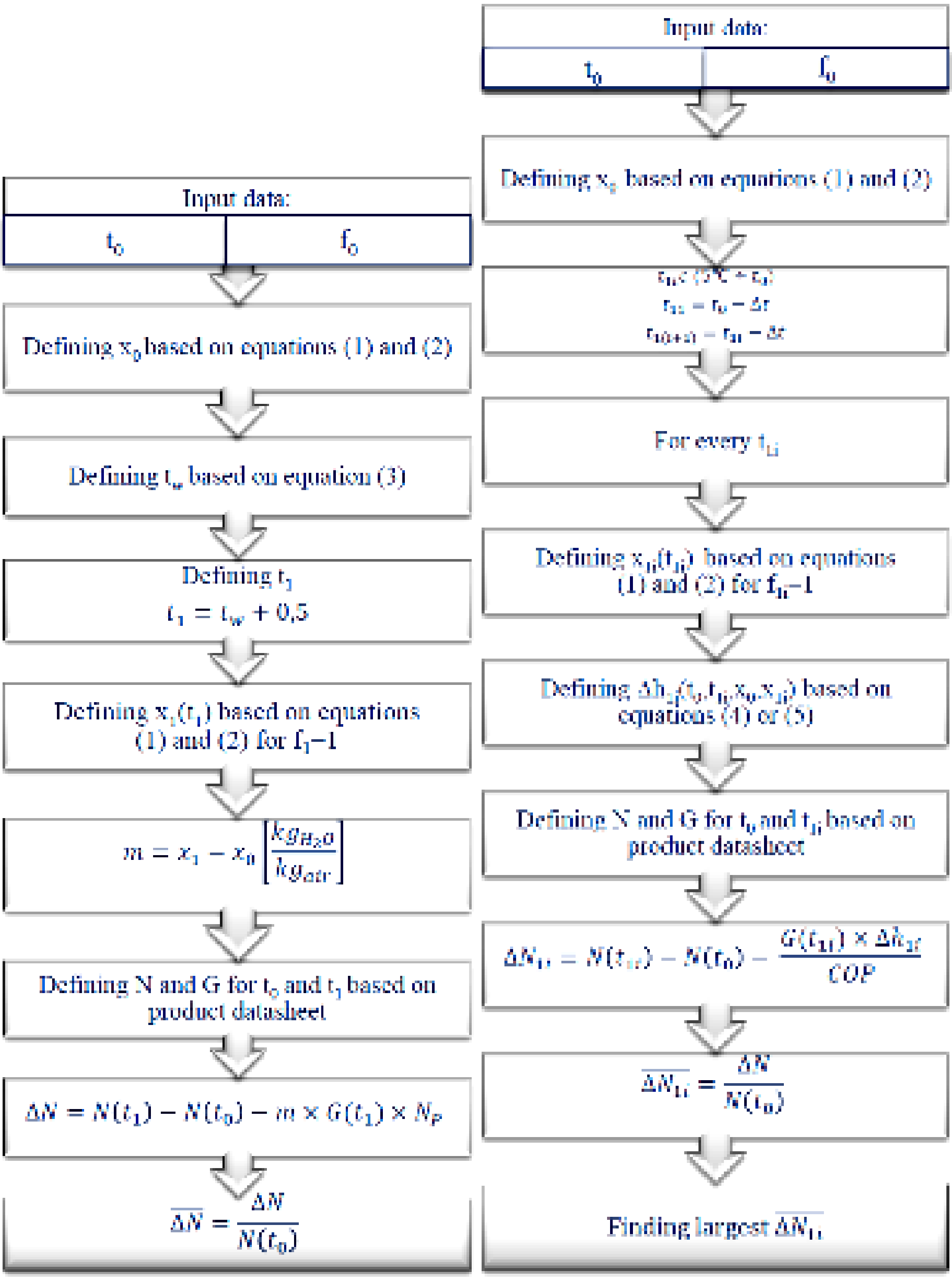

Figure 1: Sequence of actions in case of using chillers

- N_{1i} is output power for 'i' step
- G_{1i} is inlet air flow for 'i' step
- ΔN_{1i} is gas turbine power increase for 'i' step
- $\overline{\Delta N_{1i}}$ is relative power increase for 'i' step

For previous calculations following equations were used:

- Partial pressure of water in air

$$p_p = 611.2 \cdot e^{\frac{17.5 \cdot t}{241.2+t}} \tag{1}$$

where: t is temperature of air

- Specific humidity

$$x = 0.622 \frac{f \cdot p_p}{p - f \cdot p_p} \tag{2}$$

where: f is relative humidity of air, p is pressure of air set at 1013 hPa

- Wet bulb temperature

$$t_w = \frac{241.2 \cdot \ln \frac{f_0 \cdot p_p}{611.2}}{17.5 - \ln \frac{f_0 \cdot p_p}{611.2}} \; [°C] \tag{3}$$

where: f_0 is ambient relative humidity

- Enthalpy of humid air, when $x_1 < x_0$

$$\Delta h \left(t_0, t_1, x_0, x_1\right) = [1005 \cdot t_0 + x_0 \cdot (1820 \cdot t_0 + 2257000)] - [1005 \cdot t_1 + x_1 \cdot (1820 \cdot t_1 + 2257000) + (x_0 - x_1) \cdot 4190 \cdot t_1] \left[\frac{J}{kg}\right] \tag{4}$$

where: t_0 is ambient temperature, x_0 is ambient specific humidity, t_1 is temperature of cooled air, x_1 is specific humidity of cooled air

- Enthalpy of humid air, when $x_1 \geq x_0$

$$\Delta h \left(t_0, t_1, x_0, x_1\right) = [1005 \cdot t_0 + x_0 \cdot (1820 \cdot t_0 + 2257000)] - [1005 \cdot t_1 + x_0 \cdot (1820 \cdot t_1 + 2257000)] \left[\frac{J}{kg}\right] \tag{5}$$

7. Results

The highest line on the graphs show the results when ambient relative humidity was set at 30%. Each next one below corresponds to a relative humidity increase of 10 percentage points until 80% relative humidity is reached.

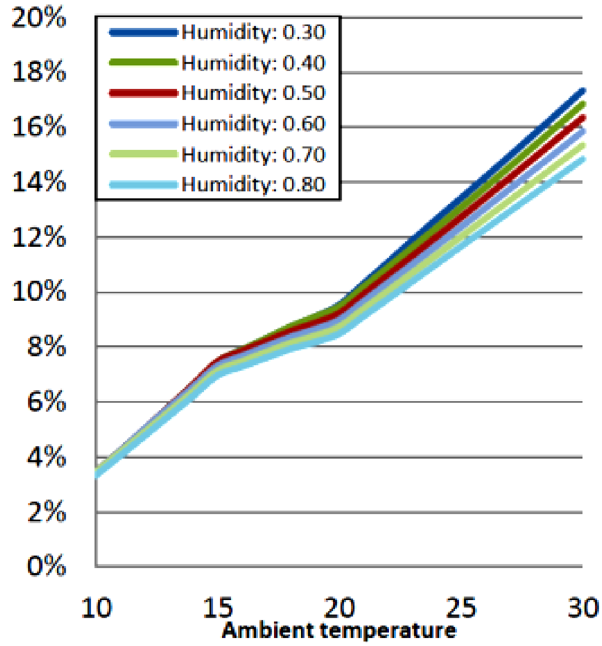

Figure 2: Relative increase in gas turbine power with cooling by chillers

Rolls Royce RB211

The first examined gas turbine is an aeroderivative turbine, Rolls Royce RB211, with nominal power output of 32 MW.

Fig. 2 presents the relationship between the power gained from cooling by chillers and the ambient temperature for each level of humidity. Compared to the other gas turbines examined, which are not high power, the slower increase in power is noticeable at higher ambient temperatures.

In Fig. 3, it can be seen that in the case of evaporative cooling the relative gain in power output for high humidity levels changes slightly with the increase in ambient temperature, which leads one to the conclusion that the use of this type of cooling would be ineffective in a high humidity hot climate.

The relative increases of the power output for this gas turbine in both cases are smaller than for another gas turbine of the similar power output (Siemens SGT-750), examined later on in this article.

General Electric 10-1

The turbine examined next was the General Electric 10-1 with nominal power output of 11.25 MW. It

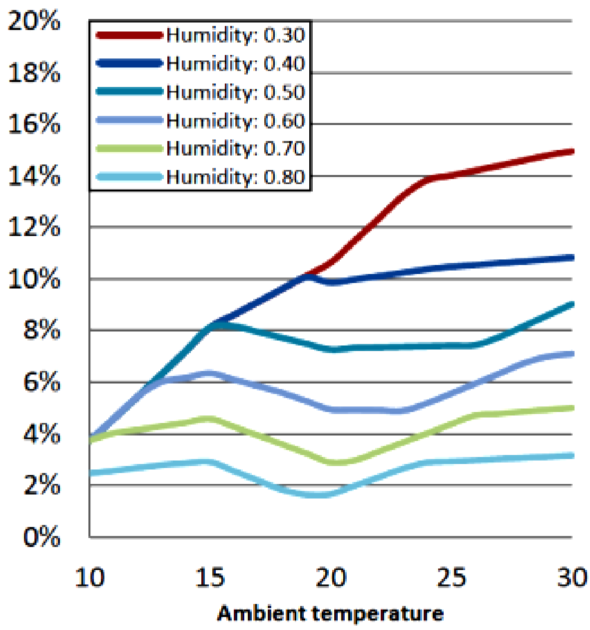

Figure 3: Relative increase in gas turbine power with cooling by evaporative coolers

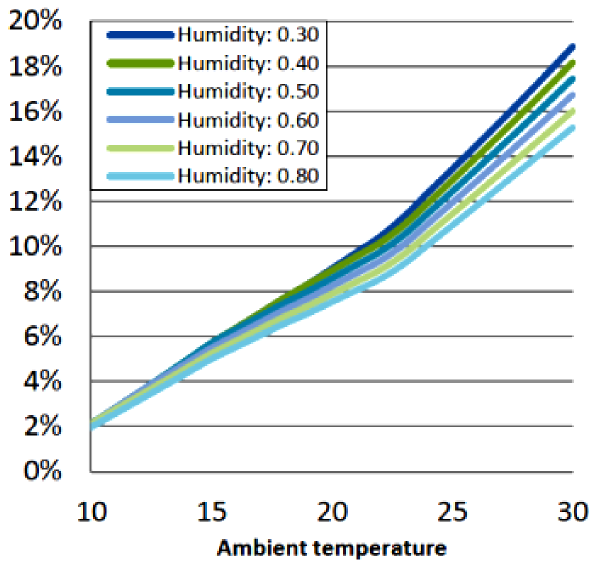

Figure 4: Relative increase in gas turbine power with cooling by chillers

is a small turbine designed to work in European systems. The relationship presented in Fig. 4 between power increase in the case of cooling by chillers and ambient temperature is almost linear. With evaporative cooling, as shown in Fig. 5, power increase slowly alongside the increase in ambient temperature, even for high humidity levels.

Siemens SGT-750

The Siemens SGT-750 turbine with nominal power output of 35.93 MW was examined. Fig. 6 shows that for ambient temperatures higher than 15°C the power gained by chiller cooling grows rapidly alongside the increase in temperature, reaching an 18–22% increase in power output at the ambient temperature of 30°C for various humidity levels. Based on that relationship it can be concluded that cooling inlet air with chillers is very effective for this turbine in hot climates. In Fig. 7 the significant difference between the results of evaporative cooling for high and low humidity levels is noticeable.

Siemens SGT6-PAC 5000F

The last turbine considered was the high power gas turbine Siemens SGT6-PAC 5000F, with nominal power output of 196 MW. Fig. 8 depicts the results of cooling by chillers and Fig. 9 the results of evaporative cooling. Compared to the gas turbines examined before, the relative gain in output power of this gas turbine in both types of cooling are smaller. However, considering that this is a high power turbine, even a smaller power increase in terms of percent points amounts to an actual gain of up to 25–30 MW, which can have a significant impact on the power system.

Siemens SGT6-PAC 5000F in combined cycle

The combined cycle of two Siemens SGT6-PAC 5000F gas turbines and one steam turbine has a total nominal power output of 593 MW. The power increases resulting from both types of cooling (by chillers in Fig. 10 and evaporative cooling in Fig. 11) are the smallest of the turbines examined. This is caused by the fact that the power output of the combined cycle is less dependent on ambient temperature than the power output of a simple cycle gas turbine.

8. Conclusion

The graphs above demonstrate that evaporative cooling is the right solution in climates with low relative humidity. There, evaporative cooling of inlet air with ambient temperatures in excess of 20–25°C has a similar effect to cooling by chillers, achieving generally an increase in output power of over 10%. Such

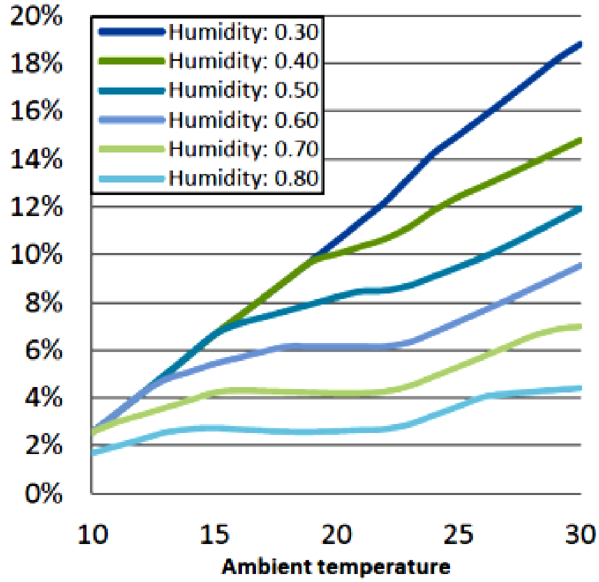

Figure 5: Relative increase in gas turbine power with cooling by evaporative coolers

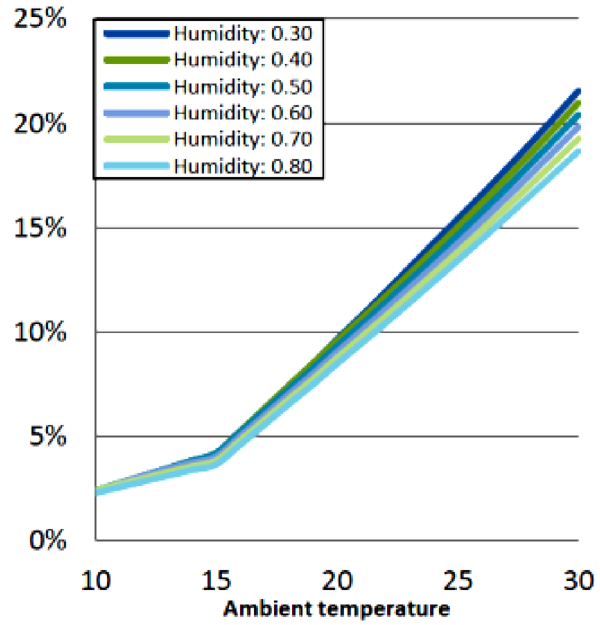

Figure 6: Relative increase in gas turbine power with cooling by chillers

ambient conditions are uncommon in Poland. In high humidity conditions and in climates where relative humidity varies across a wide range, it is sensible to use chillers for cooling. In this solution there is enhanced gas turbine power independence from the humidity and temperature of ambient air, because operation of the chiller is not limited by the wet bulb temperature. Therefore, there is greater stability of maximum output power, which reduces the risk of generating less power than contracted. Similar conclusions can be drawn with regard to the combined cycle. Lowering the inlet air temperature causes an increase in the flow of flue gases, but also decreases their temperature. These changes have opposite effects on turbine performance. With larger flow, the power of the steam turbine increases but with lower flue gas temperature it falls. Therefore, the relative increase in power output of the combined cycle gained from inlet air cooling is lower than in a simple cycle with the same gas turbine. Still, power increase of 6–8% is gained in typical summer conditions by cooling by chillers.

The studies conducted show that the use of inlet air cooling is reasonable in hot climates. Cooling by chillers can be used in climates with variable humidity, while in location where humidity is constantly low, it is worthwhile considering the use of evaporative coolers.

The use of inlet air cooling is unjustified in moderate climates, where annual average temperatures are relatively low.

With the current national power generation structure based generally on coal-fired power plants, whose performance does not depend on ambient conditions, the decrease in the power output of gas turbines during summer has an insignificant impact on available power in the Polish power system. Therefore, the advantages of inlet air cooling in present Polish conditions are insufficient when set against the investment cost involved. Nevertheless, with greater reliance to be placed in future on power generated by gas turbines, inlet air cooling could become more attractive.

References

[1] M. Jonsson, J. Yan, Humidified gas turbines—a review of proposed and implemented cycles, Energy 30 (7) (2005) 1013 – 1078. doi:10.1016/j.energy.2004.08.005.

[2] J. E. Kraft, D. Eberlein, Inlet air cooling systems boost summer peaking capacity at we, Power Engineering 103 (11) (1999) 74.

[3] M. Farzaneh-Gord, M. Deymi-Dashtebayaz, Recoverable energy in natural gas pressure drop stations: A case study of the khangiran gas refinery, En-

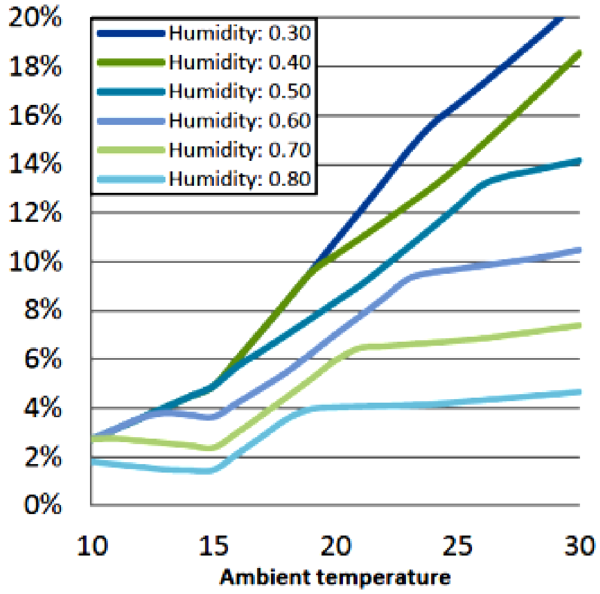

Figure 7: Relative increase in gas turbine power with cooling by evaporative coolers

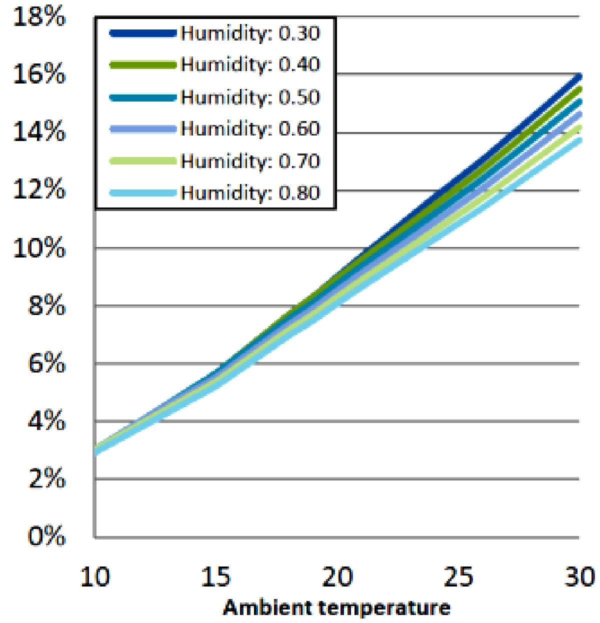

Figure 8: Relative increase in gas turbine power with cooling by chillers

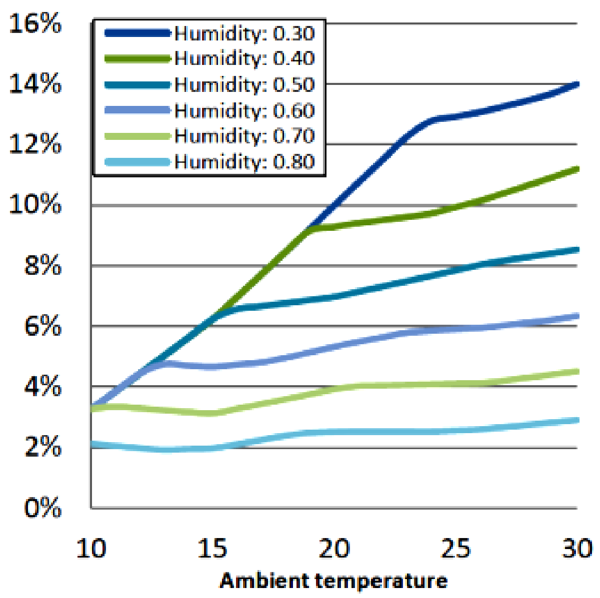

Figure 9: Relative increase in gas turbine power with cooling by evaporative coolers

ergy, Exploration & Exploitation 26 (2) (2008) 71–82. doi:10.1260/014459808785260508.

[4] DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009.

[5] M. Farzaneh-Gord, M. Deymi-Dashtebayaz, Effect of various inlet air cooling methods on gas turbine performance, Energy 36 (2) (2011) 1196 – 1205. doi:10.1016/j.energy.2010.11.027.

[6] Diesel & Gas Turbine Worldwide: Inlet Air Cooling. June 2001.

[7] T. Giampaolo, MSME, PE, Gas Turbine Handbook: Principles and Practices, 3rd Edition, The Fairmont Press, 2006.

[8] C. Strumiłło, Podstawy teorii I techniki suszenia, WNT, Warszawa, 1983.

[9] Rolls Royce, USA, RB211 Gas Turbines (2011).

[10] Siemens AG Energy Sector, Sweden, Meet the SGT-750 (2010).

[11] Siemens AG Energy Sector, USA, Siemens Gas Turbine SGT6-5000F Application Overview (2008).

[12] GE Oil & Gas, Sagraf, GE10-1 Gas Turbine (2005).

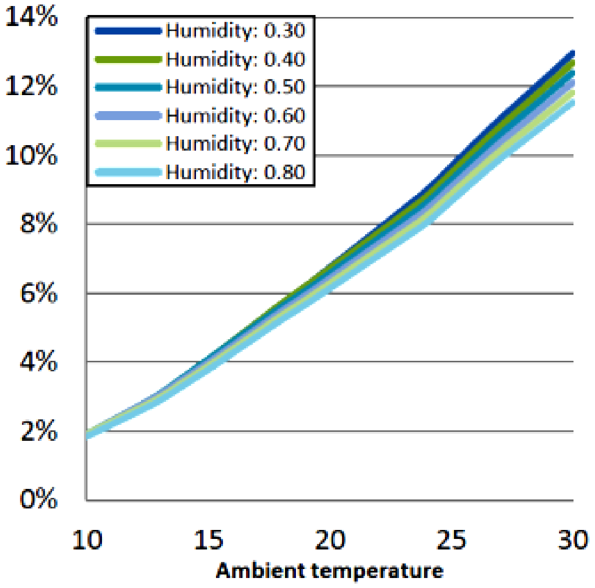

Figure 10: Relative increase in power of a gas turbine in combined cycle with cooling by chillers

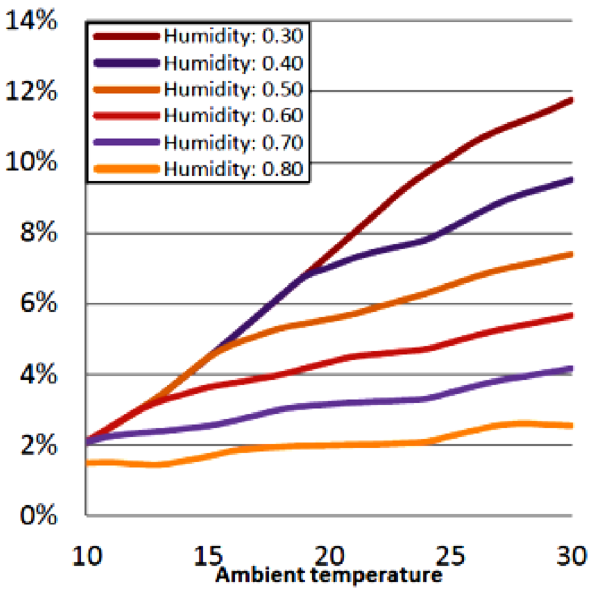

Figure 11: Relative increase in power of a gas turbine in combined cycle with cooling by evaporative coolers