The Increased Importance of Evaporative Coolers for Gasturbine and Combined-Cycle Power Plants

Introduction

The development and the design of gas turbines has undergone a rapid development during the past ten years, which led to large improvements in power output and efficiency, in particular for the large units. In parallel, the specific emissions were reduced through low-NO_x technology and also prices fell by approximately 50 % within a few years, so that investment cost incurred by gas turbine and combined-cycle power plants are the lowest of all thermal power plants.

The effects of evaporative cooling on the minimum available power output of gas turbines are described below, and the climatic conditions in the various parts of the world are outlined in detail. It is shown how essentially “low tech” can improve the performance of “high tech” gas turbines.

Decline of Gas Turbine Output at Increasing Ambient Temperatures and Increasing Power Demand

The available output of a gas turbine depends strongly on the temperature and pressure of the process air, i.e. the ambient temperature and pressure, so that in particular at high ambient temperatures, the available output is considerably reduced. This reduction depends on the type of turbine and on the absolute ambient temperature and reaches from 0.5 % /°C to more than 1 % /°C of the ISO output, which is defined at 15 °C. Thus, there is a power output reduction of 7.5 to 10 % (compared to ISO output) at 30 °C ambient temperature for the most commonly used turbine types. For aeroderatives like the LM 6000, the reduction can amount to more than 35 % of the ISO output in the desert at more than 50 °C. In parallel, the heat rate increases by approximately 0.2 % /°C of increased ambient temperature.

In contrast with Germany, where the peak demand occurs in the winter months, the peak demand in many warmer countries occurs in particular during the afternoon hours, when the ambient temperatures are high and the air conditioning systems require much power. In parallel, the available capacity of the operated gas turbine and combined-cycle power plants drops at these high external temperatures.

An improvement of this situation is offered by the cooling of the inlet air that leads to an increased density of the inlet air, giving in turn a higher combustion air mass flow and finally leads to a higher power output. There are various methods of cooling, with the evaporative cooling – also called adiabatic cooling – being by far the most inexpensive cooling tool to create the most inexpensive specific power increase (cost per additional power output). Today this is realized by a medium cooler with a large surface area or high pressure fogging systems (HPFS).

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Climatic Potentials

The target of these technologies is to transfer a given air condition A by the evaporation of water into a highly saturated condition B, the temperature B being close to the wet bulb temperature of condition A (see also h,x diagram, which is a psychrometic diagram in Figure 1). The displayed potentials can be used with an efficiency of 90 to 98 % [$(T_{in}-T_{out})/(T_{in}-T_{saturation})$] with the aid of the discussed technologies, so that downstream of the cooler an air condition is achieved, which is just a few tenths of a degree C above the wet bulb temperature, which is the limit for this technology.

The evaluation of worldwide climatic data [1] shows that the maximum wet bulb temperatures fluctuate heavily depending on location and time of the year, with the highest wet bulb temperatures existing in the Gulf area in August, where peaks reach 31 °C. In tropic countries around the equator, a maximum of 26 to 27 °C is measured for the wet bulb temperature. In Germany, maximum wet bulb temperatures are smaller than 24 °C. The said maxima are reached only for a few hours per year (except for the tropics), the majority of the hot days or hot periods of the day have maxima of 1.5 to 3 °C lower than the absolute maxima. Also in the Gulf area, 27 to 28 °C wet bulb temperature are not exceeded for 9 to 10 months.

It is important to know that at the warmest time of the year or day, the difference temperature between ambient temperature and its wet bulb temperature is at its maximum or close to it. This means that evaporative cooling has the biggest effect at the highest ambient temperature or at temperatures close to the highest ambient temperature.

Table 1 shows the maximum ambient temperatures in the various regions and the maximum cooling potentials that can be achieved at maximum ambient temperatures or temperatures close to the maximum temperatures.

The majority of the gas turbines has a specific power degradation of the ISO power output of around 0.65 %/°C, so that the relative improvement for the listed regions amounts to 7 to 17 % (for aeroderatives much higher) of the ISO power output. The average temperature reduction (24 h) is generally not more than 4 to 5 °C over the year, which means an average power increase of approximately 2.5 to 3 %. At ambient temperatures below 10 °C it makes little sense to operate an evaporative cooler, because there is usually not more than a 2 to 3 °C potential, in

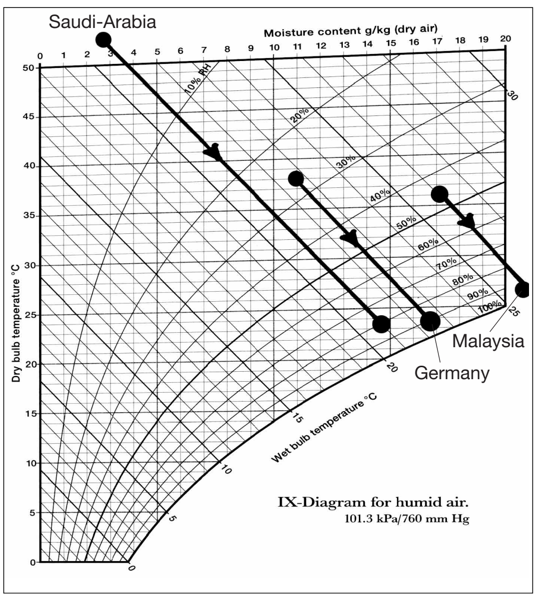

Figure 1. Maximum cooling potentials in various areas of the world.

Table 1. Maximum ambient temperatures and maximum cooling potentials.

Location	Germany	Gulf Region (coastal area)	Saudi Arabia (inland)	Tropics	South. USA
Max. Temp. in °C	38 - 40	46	55	36 - 38	44
Cooling potential in °C	14 - 16	14 - 15	26 - 28	10 - 12	18

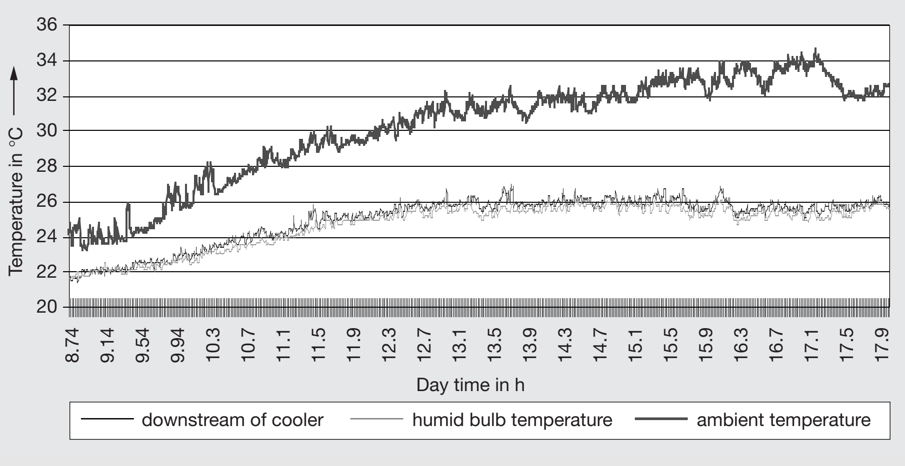

Figure 2. Typical temperature flows upstream and downstream of evaporative cooler in Malaysia (GT 13 E2).

addition there would be a conflict with the anti-icing system at temperatures below 5 °C downstream of the cooler (Figure 2).

Evaporative coolers have occasionally been installed and operating for more than 15 years upstream of gas turbines, but only during the past 5 years could a steady growth in the numbers of annual installations be observed, because the decision-makers were not aware of the additional power potential, and/or both customers and the power industry were unable to interpret weather data correctly.

Economy

The present steady growth in annual installations is above all enforced by the results of commercial calculations. Even in the tropics, a gas turbine with 165 MW power output (ISO) and an evaporative cooler produces over a day's period 4 to 7 MW, sometimes up to 10 MW, more than without a cooler. With an additional capacity of 10 MW, some independent power producers achieve additional incomes in 1 to 2 months that pay back the investment costs of the evaporative cooler. In Germany, the evaporative cooler usually pays back after 1 to 2 years, if performance payments had been agreed upon between seller and buyer. Today, the minimum cost of a complete medium cooler equipped with PLC and redundant pumps including transport and erection, amounts to approximately US$ 250,000 to 300,000 for a 165 MW unit, while for a high pressure fogging-type system, the price is lower by approximately 10 to 15 %. Considering a maximum power increase by the cooler at higher external temperatures of only 5 MW, the equivalent value for the installed gas turbine capacity is approximately US$ 1,250,000 even at the presently low investment costs of only 250 US$/kW for gas turbine power plants. Taking the more realistic assumption of additional 10 MW into consideration, the equivalent gas turbine value is US$ 2,500,000. This comparison shows the relatively low investment costs for additional power compared to (the already low) specific investment costs of a gas turbine (Table 2).

Designs

Designed as a medium cooler (Figure 3), the evaporative cooler can be installed in front or behind the air filters. Designed as an HPFS, it is highly recommended to install the cooler downstream of the air filters, to avoid loading the filters with droplets. The medium cooler releases only droplet-free air and can be installed upstream of the air filters.

The medium cooler is typically designed with an efficiency of 90 to 95 % and consists of a 300 mm deep medium (Figure 4), possibly followed by a droplet separator, that, depending on the location upstream or downstream of the filters, is 60 to 170 mm deep, so that the total depth of the design is 340 to 630 mm. The media is flooded with

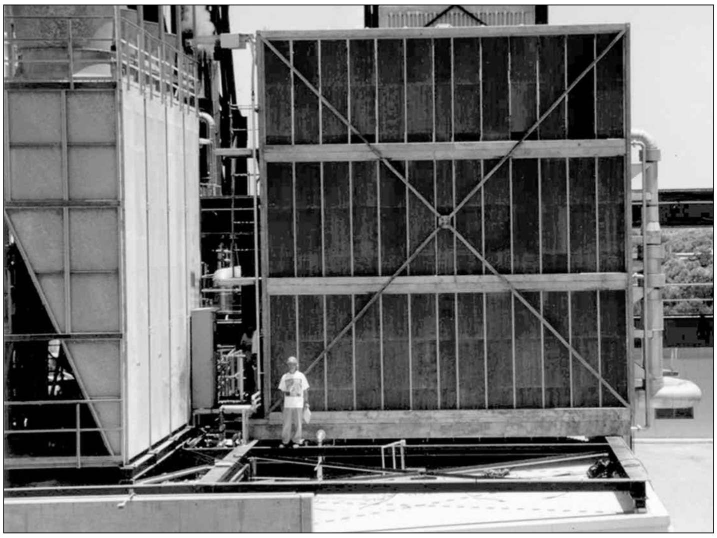

Figure 3. Retrofit of precooler 2 x GT 8 in Chania/Crete.

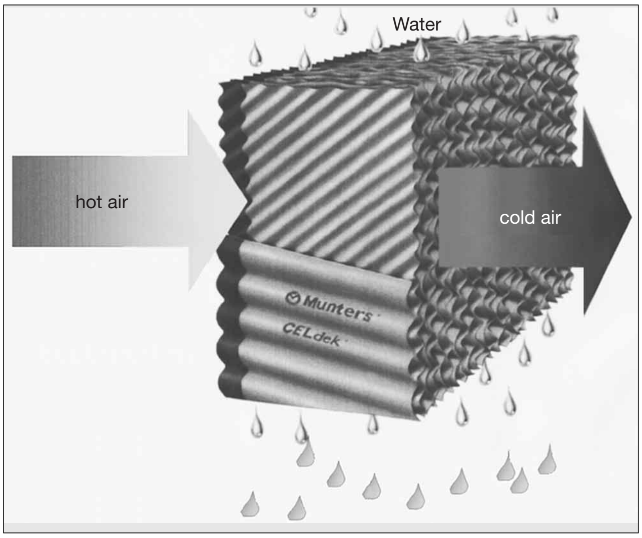

Figure 4. Functioning principle of the medium cooler.

Table 2. Capacity increase and water consumption in a Frame-6 gas turbine in Madrid/Spain.

Month	Cooling hours	Average temperature reduction in °C	°hours in h-°	Max. temp. in °C	Max. temp. reduction in °C	Cooler capacity „off" in MW	Cooler capacity „on" in MW	Water evaporation in m³	Max. water evaporation in m³/h	Additional energy in MW/h
Jan.	143	4.7	670	20	8.3	38.70	40.87	137	1.702	174
Feb.	201	4.9	995	20	7.8	38.70	40.74	203	1.599	258
Mar	367	5.6	2 056	25	11.4	37.26	40.21	420	2.322	534
Apr.	464	5.6	2 618	31	14.4	35.82	39.56	534	2.941	679
May	641	6.0	3 825	34	13.9	35.10	38.71	781	2.837	993
June	708	7.2	5 092	39	16.4	33.66	37.92	1 039	3.353	1 322
July	737	9.0	6 637	42	19.0	32.93	37.86	1 354	3.869	1 722
Aug.	741	8.7	6 451	42	18.5	32.93	37.72	1 317	3.766	1 674
Sept.	703	6.9	4 878	39	16.9	33.66	38.05	996	3.456	1 266
Oct.	607	4.9	3 004	31	11.4	35.82	38.77	613	2.322	780
Nov.	345	4.0	1 368	25	6.8	37.26	39.03	279	1.393	355
Dec.	194	4.0	781	20	6.8	38.70	40.47	159	1.393	203
Total	5851	6.0	38 373	31	13	36	39	7 832	3	9 959

Suction volume flow:	114	m³/s
Cooling efficiency:	91	%
Supply capacity:	40	MW of turbine to ISO at 15 °C suction temperature
Heat rate:	11 000	MJ of turbine to ISO bei 15 °C suction temperature
Capacity increase per °C of cooling:	0.65	% per °C
Heat rate reduction per °C of cooling:	0.18	% per °C

water and is available in two types, based on impregnated paper fibres and on glass fibre, i.e. flammable and non-flammable. Alternatively, between medium and droplet separator, there is a maintenance walkway with 600 to 800 mm depth, so that the complete module including the walkway is up to 1500 mm deep. In case of an installation downstream of the filters, the droplet separators form a mechanical barrier against any forein matter that could move with the air stream towards the gas turbine, and separate 99 % of droplets larger 25 µm, if it should release from the cooler, either caused by aging or by operation with water that is not in accordance with the specification. At velocities below 2.8 m/s and a cooler installation upstream of air filters, it is not necessary to install droplet separators downstream of the medium cooler.

The medium cooler is completed by a tray or a tank, which is either integrated into the design of the cooler, or is separately built on a pump/tank skid on the 0.0 level of the power plant on a concrete foundation. This skid contains also the controls and the connections for fresh water, drain, feed and return water as well as the wiring connections.

The pump skid part of the HPFS is also placed on a concrete foundation below the air filter house and has a connection for fully demineralized water. After passing a fine filter, this water is pressurized up to 70 to 100 bar and distributed into various pipes through which it flows to the filter house. Through up to approximately 1500 nozzles (at bigger gas turbines) (Figure 5), it is sprayed into the inlet combustion air to evaporate in the air stream and cool the air down towards the wet bulb temperature before entering the compressor.

The principal target pursued is the same as with the medium cooler, i.e. to increase the humidity up to 90 % or more and to cool it simultaneously down. By using multiple, possibly also variable-speed drives, the water mass flow is controlled in a way that the target humidity (and with that a temperature close to the wet bulb temperature) is achieved. A minimum of 8 steps, better 12 steps, is required to realize a target humidity of over 90 %, but on the other hand not to overspray the air with droplets. The main components of an HPFS system are the precise water mass flow control with several pumps, which starts with a precise measurement of the ambient conditions, together with the high number of nozzles. The air velocities that usually do not exceed 4 m/s in air filter houses, are not critical for the HPFS operation, not even, if the velocities are higher than 4 m/s, while a medium cooler is only able to properly handle air velocities of up to approximately 3.6 m/s based on the latest developments in the field of medium coolers.

The humidity control is no problem for the medium cooler, because the humidity efficiency is always constant and lower than 100 %, as the total surface area that evaporates water remains constant. If not influenced by aging or by improper design, the medium cooler releases droplet free air, while the HPFS nozzles, within their spectrum, always produce droplets up to 100 to 120 µm, which cannot completely evaporate after the smaller droplets (5 to 30 µm) have been completely evaporated and the humidity of the air has increased already, so that there is only a small evaporation potential left and the residence time in the air before entering the gas turbine is too short (few seconds) as shown in Figure 6.

Water Quality

The required water quality is another substantial difference between the two systems. Because the evaporated droplets of an HPFS are not permitted to leave residues in the air, because they would contaminate the combustion air, which would lead to compressor fouling, high temperature corrosion etc.

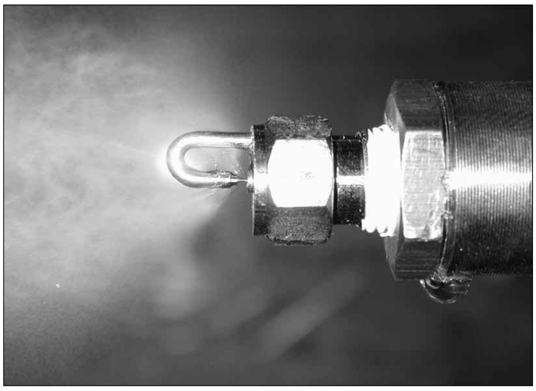

Figure 5. Fine-spray HP nozzle in operation.

Therefore the HPFS can be operated only on fully demineralized water. The medium cooler, however, does not need demineralized water at all, because it evaporates demineralized water anyway, leaving the residues in the circulation water from where they are removed with the blow down water.

Pressure Loss

The HPFS causes only a minor pressure loss in the air intake system of around 10 to 20 Pa, while the pressure loss over a medium cooler amounts to 60 to 150 Pa including droplet separator (Figure 7).

The pressure drop becomes relevant for systems where the evaporative cooler is s operated less than about 500 h annually, because the pressure drop for the HP fogging-type cooling for the remaining time is minimal, which is reflected in the slightly higher heat rate of the gas turbine compared to the medium cooler (approximately 0.02 % higher). If both coolers are in operation, there is no significant difference regarding the heat rate between the two, because the HPFS has a power demand for the HP pump of approximately 15 to 30 kW for a 40 MW gas turbine [2] and causes pressure drop losses of another 10 kW, while the medium cooler causes approximately 40 kW power loss through pressure drop and has a power demand of approximately 2 kW. Both coolers, however, increase output by 200 kW/°C of cooling.

Operating Cost

A significant part of the operating cost of an evaporative cooler is made up by water costs. If a cooler is required for many operating hours (approximately more than 25 % of operating hours), the medium cooler is usually the cheaper solution, because the water costs for demineralized water necessary for the operation of an HPFS, compared to "normal" water from a well or precleaned river water, in particular taking the investment costs for the demin water plant into account, are relatively high. In addition, the wear of the mechanically driven parts of the HP piston pumps is greater than that of the almost maintenance free centrifugal pumps. The media for the medium cooler have a lifetime of 4 to 8 years, depending on the water quality used. The nozzles for an HPFS may last as long as 4 to 8 years, most likely, however, their lifetime will be shorter due to the abrasion on the nozzle hole. As an indicative recommendation, a gas turbine using the evaporative cooler for less than 10 % of its operating time, should be equipped with an HPFS, if demin water is available. However, the total evaporative cooler lifetime cost must be calculated for each project based on the real water prices, because the water prices are very different all over the world.

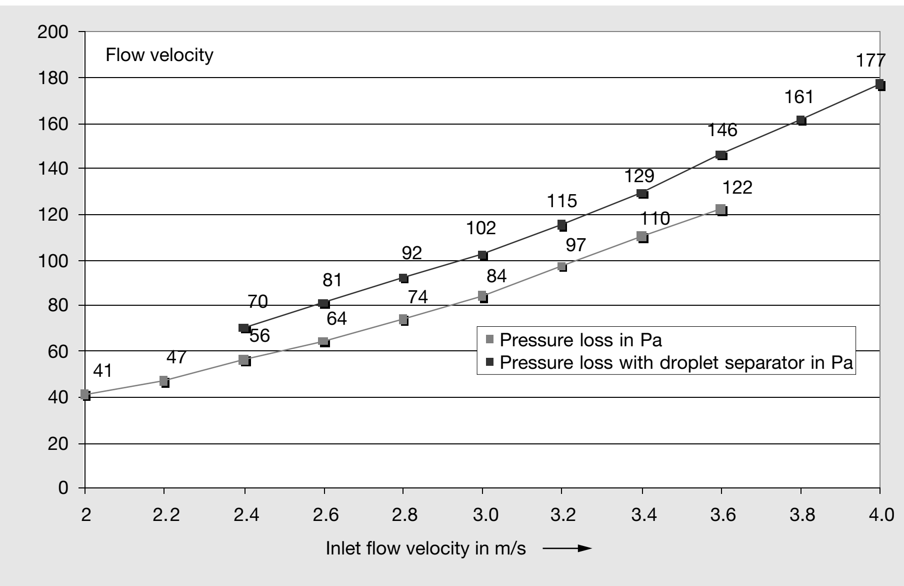

Figure 7. Pressure drop over air velocity for a medium cooler.

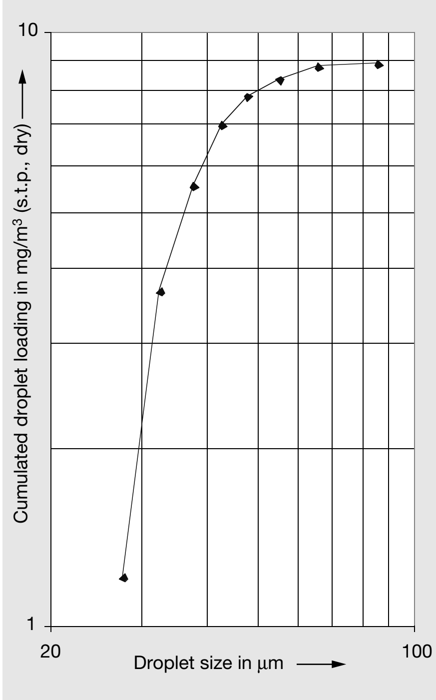

Figure 6. Remaining droplet content downstream of a fine-spray nozzle after 2 s in air. Air conditions in the measuring point relative humidity of 41 % at a temperature of 18.2 °C, basic air temperature 24.5 °C (to [4]).

Conclusion and Outlook

It is very interesting that the "low tech" tool "evaporative cooler" has relatively late gained in importance for the power output increase at higher ambient temperatures, though the principle has been known for a long time and also the relevant weather data have been accessible since long.

The installation of gas turbine and combined-cycle power plants has particularly increased in North America during the past two years, and 35 to over 50 % of the delivered stationary gas turbines are already equipped with an evaporative cooler. It is interesting to see, how fast this percentage will further increase in North America and whether the trend will also continue in Europe and Asia.

Bibliography

[1] Results of calculations with the computer programme KOOLGAS, Munters Corp.

[2] Calculated for a GE Frame with 40 MW ISO output, by using the correction curves for temperature and humidity.

[3] Remaining water droplet content tests, calculated with the computer programme KOOLGAS of Munters Euroform GmbH, Aachen.