ASHRAE JOURNAL

Turbine Inlet Air Cooling

William E. Stewart, Jr., Ph.D., P.E.
Member ASHRAE

Increasing combustion airflow rate is a common modification to increase power and net efficiency. To get more power out of a gas turbine, simply increase the mass flow rate of air into the compressor. More air begets more power. Automobile engines use inlet air compressors (turbos). Gas turbines (also called combustion turbines because they can use natural gas, fuel oil and other fuels) use supercharging or inlet air cooling to increase the mass flow rate. Combustion turbine inlet air cooling (CTIAC) systems are commonly used to increase the airflow rate and therefore increase the power produced.

Parameters that affect the design of CTIAC installations and operations include the type of turbine, climate, hours of operation, the ratio of airflow rate to power generated, and the value of the power generated. This article discusses methods and techniques used in CTIAC applications.

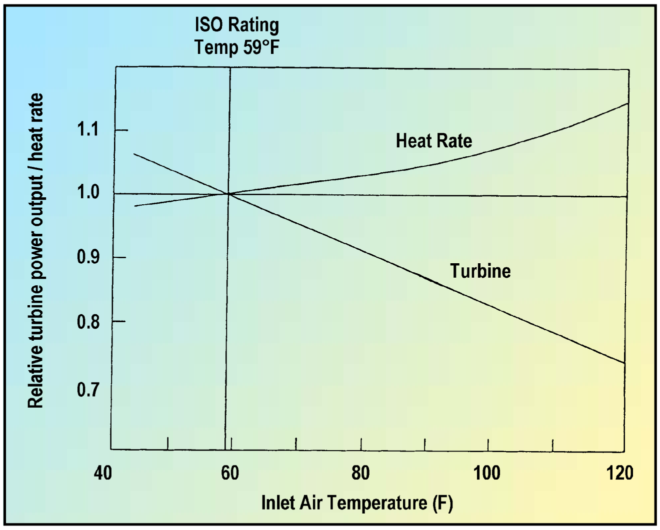

Figure 1: Typical turbine power output and heat rate versus inlet air temperature.

Increasing Capacity

The volumetric flow to most turbines is constant, and therefore increasing the air density increases the mass flow rate. A CTIAC system increases the capacity of turbine/generators by increasing the air density of the combustion air. Typically, the increased mass flow rate also decreases the rate of fuel consumed per unit of power produced (the heat rate), after all parasitic cooling power is considered.

The power produced by the turbine is nearly a linear function of air mass flow rate. By ignoring the additional mass flow from the fuel, an ideal gas the mass flow rate is:

$$m = P_1 V_1 / RT_1 \qquad (1)$$

Hence, power output is a linear inverse function of temperature.

As the inlet air temperature increases, such as on hot summer days, the capacity of a turbine decreases,[1] as shown in *Figure 1*. If the inlet air is cooled to a lower temperature, the power increases, along with increased efficiency (decreased heat rate). The approximate cycle efficiency, η, can be expressed in terms of the isentropic compression process from compressor inlet temperature, T_1, to compressor outlet temperature, T_2, as:

$$\eta = 1-(T_1/T_2) \qquad (2)$$

Hence, the efficiency also increases for decreasing T_1.

Turbines

Combustion turbine systems operate as simple cycles or as combined cycles, shown schematically in *Figure 2*. In the combined cycle, the combustion turbine operates in parallel with a steam turbine, where the steam is generated either by combustion turbine exhaust gases with a heat recovery steam generator, by supplemental firing to the turbine exhaust or by using a separate heat source.

Industrial combustion turbines are single-shaft ,heavy-duty turbines, with generating capacities of 20 to more than 250 MW, operating with natural gas or distillate oil. Aeroderivative turbines are modified aircraft engines of 500 kW to over 40 MW capacity, typically using natural gas fuel. Both types are rated at the International Standards Organization (ISO) inlet air conditions of 59°F (15°C) air temperature, 60% relative humidity, and 14.7 psi (101 L) absolute pressure (sea level), at a generator power factor of 0.9.

Industrial turbines use constant inlet air volumes, while aeroderivatives operate with multiple compressor shafts and varying air volumes. Newer turbines operate with lower airflow rates/units of power and therefore, decrease the cooling required for an incremental power increase.

Cooling Systems

CTIAC designs include turbines that operate only a few hours per year, for demonstrating power reserve or for peak demand power. Both evaporative cooling systems and thermal energy

Nomenclature

m mass flow rate	T temperature
P pressure	V volumetric flow rate
R gas constant	η thermodynamic efficiency

About the Author

William E. Stewart, Jr., Ph.D., P.E., is a principal of InterMountain Research, Olathe, Kansas. He is the Handbook and Program Subcommittee Chair for the Task Group for Combustion Gas Turbine Inlet Air Cooling. He is also the secretary of ASHRAE Technical Committee 6.9, Thermal Storage.

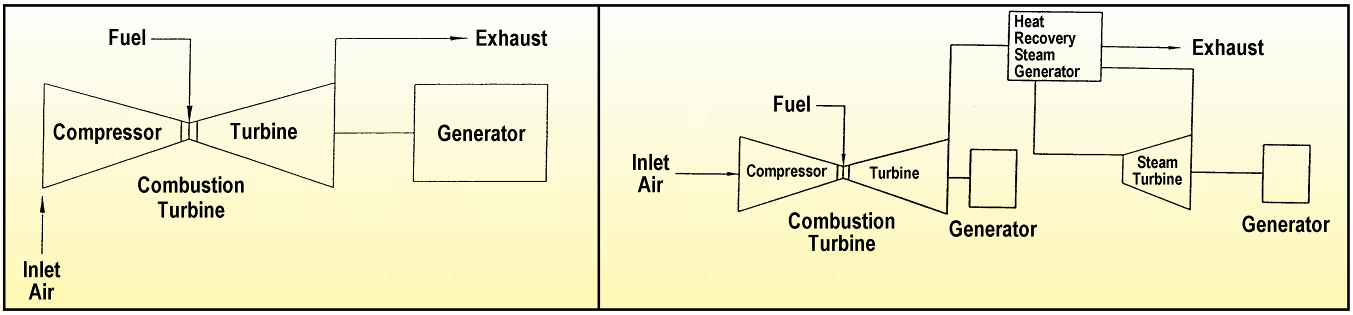

Figure 2: Typical combustion turbine simple (left) and combined cycle systems (right).

storage (TES) systems allow cooling during turbine operation without coincident parasitic power, except for pumps. TES systems allow the use of small capacity refrigeration systems, operated only during off-peak hours.

For turbines operating continuously or several hours per day, fuel costs and availability are important factors, and favor on-line cooling systems, such as evaporative systems or refrigeration systems without thermal storage.

The most prevalent CTIAC system is evaporative cooling, using wetted media, due to low installation and operating costs. Some CTIAC installations use refrigeration systems, operated continuously or with TES.

An ideal evaporative cooling process occurs at constant wet-bulb temperature, cooling the air to 100% relative humidity. The inlet warm air is partly in contact with the liquid water and transfers heat to the liquid water, evaporating part of the liquid water into vapor. As the air transfers heat to evaporate the liquid water, the temperature of the air decreases and results in the air cooling effect.

As an example, an evaporative cooling process is shown in *Figure 3*, where the incoming, ambient air is shown as Condition 1, which is 100°F (38°C) and 30% relative humidity. As the liquid water evaporates, cooling occurs along a line of constant wet bulb, approximately 74°F (23°C). If the process reaches saturation, the air-water vapor mixture is at Condition 2, where the temperature is 74°F (23°C). The typical evaporative cooling system allows the air-water vapor mixture to reach 85 to 95% of the difference between the dry bulb air temperature and the wet bulb temperature. The 90% condition is shown as 3. The mixture temperature at Condition 3 is warmer than at saturation, approximately 77°F (25°C).

Evaporative cooling can also be used before or after cooling coils. For example, air is sensibly cooled to a lower dry-bulb temperature, for example 85°F (29°C), as 1-4 in *Figure 3*, then evaporatively cooled along a line of constant wet bulb of 70°F (21.1°C). For 90% effectiveness, the outlet air temperature is 71°F (22°C), Condition 5. The other option is to first evaporatively cool the air from Condition 1 to 85°F (29°C), Condition 6, and then sensibly cool the air. To reach the same inlet air temperature of 71°F (22°C) from Condition 6 using a cooling coil, the air undergoes both sensible and latent cooling to Condition 7, due to coil cooling characteristics. If a combination of sensible cooling (cooling coils) and evaporative cooling are used, sensible cooling should be used first and then evaporative cooling to reach the minimum temperature without having latent cooling (condensation) by the cooling coils.

A secondary fluid cooling (chilled water, brine or refrigerant) process is also shown in *Figure 3*, where the air-water vapor mixture is being cooled from the same initial condition, Condition 1. The process decreases the enthalpy (and temperature) of the air-water vapor mixture as the mixture is cooled. The water vapor content (the humidity ratio) remains constant as the mixture decreases in temperature to Condition 8, 73°F (23°C). Continued cooling will follow the cooling coil performance curve. If cooled to 40°F (4°C), the condition is shown as Condition 9. Condition 9 represents a mixture where the relative humidity of the air is near 100% with a decreased humidity ratio, having forced much of the water vapor to condense.

A chilled water (or brine) system can be utilized in conjunction with thermal energy storage. The TES system is usually justified, from a cost standpoint, only for turbines that operate a few hours per week or to increase reserve power. A chilled water system will probably have a higher capital cost and use more energy than a refrigeration cooling coil system because of the secondary fluid loop, the pumping required, and the increased size of cooling coils.

The chilled water system, though, requires less refrigerant piping and inventory, and is therefore less susceptible to refrigerant leakage. Thermal storage allows the reduction of refrigeration equipment size and reduces on-peak parasitic energy, which has a significant effect upon system economics.[3] Parasitic loads for a TES system that operates only a few hours per week will usually not severely impact the economic value of a CTIAC system.

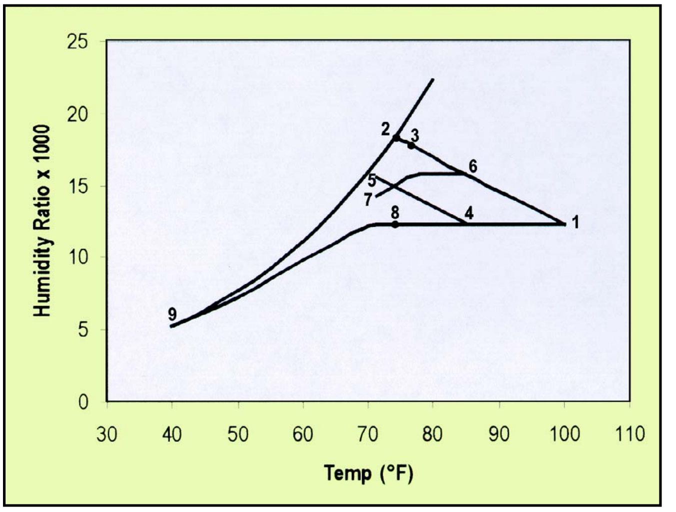

Figure 3: Evaporative and coil cooling processes.

A refrigerant cooling coil system utilizes either vapor compression or waste heat operated absorption. The air cooling process is identical to the chilled water process shown in *Fig-*

ure 3. The DRC system can provide cooling during all hours of turbine operation. The refrigerant system must be sized to meet the peak cooling required and therefore the refrigeration system is larger than for a storage system.

Installations

The turbine/generator at a Nebraska company has an ISO rating with distillate oil fuel of 59.8 MW and a peak rating of 65.2 MW. Inlet air cooling, from an air ambient temperature of 100°F to 40°F (38°C to 4°C), produces a net power increase of approximately 12 MW or about 21%.[2] The Nebraska site uses the first CTIAC system with ice storage.

The aeroderivative turbine at a San Diego site generates both electricity and steam. The refrigerant system operates continuously providing an inlet air temperature of 43°F (6°C), increasing the capacity from the ISO rating of 30 MW to 37.5 MW.

A generating station near Kansas City utilizes two industrial turbines with evaporative cooling. The turbines are ISO rated at 48 MW. At the design ambient conditions of 97°F and 75°F (36°C and 24°C) wet bulb, the evaporative cooling system increases the capacity of each turbine by 3.5 MW.

Advantages of CTIAC

Capacity Enhancement. Use of CTIAC for newer turbines, with lower airflow rates per unit of power generated, is even more economical than for older turbines, as the lower flow rates require less cooling capacity to lower inlet air temperatures, resulting in smaller evaporative coolers, refrigeration equipment and thermal storage systems.

Heat Rate Improvement. Fuel mass flow rates increase with increasing inlet air flow and increasing turbine output, but typically at a smaller rate. CTIAC systems can be used primarily for the improved heat rate and the corresponding fuel cost savings per unit of power produced.

Turbine Life Extension. Turbines operating at lower inlet air temperatures have extended life and reduced maintenance. Lower and constant turbine inlet air temperatures reduce the wear and tear on turbines and turbine components.

Increased Combined Cycle Efficiency. Decreased inlet air temperatures result in decreased exhaust gas temperatures, potentially decreasing the capacity of the heat recovery steam generators for steam turbines and absorption equipment. The greater airflow rate of a CTIAC system, though, usually results in an overall increase in capacity, as the effect of increased exhaust mass flow rate exceeds the effect of decreased temperature.

Delayed New Generation. With a CTIAC system with increased generation capacity, the requirement for additional actual or reserve generation capacity can be delayed.

Base Load Efficiency Improvements: Thermal Storage. An ice or chilled water TES system can help level the base load of a power generation facility and produce stored energy by electric chiller equipment during off-peak periods, which tends to increase the efficiency of power production. Electric chillers operated at cooler night temperatures have a higher efficiency and operate at reduced condenser temperatures, which can also use less source energy.[4]

Efficiency Improvements: Base Loaded Turbines. When maximum power is desired every hour of the year, a continuous CTIAC system is justified in warm climates to maximize turbine output and minimize heat rate.

Other Benefits and Considerations

- CTIAC systems require additional space and increase maintenance.
- Evaporative media or cooling coils pose a constant inlet air pressure loss, though the cooling systems may be used during warm weather. Evaporative media also acts to filter the inlet air.
- CTIAC systems that reduce the air temperature below saturation can produce a significant amount of condensed water–potentially a valuable resource, that can be used to provide makeup water for cooling towers or evaporative condensers.
- CTIAC systems are energized only when required.
- Emissions can decrease due to increased overall efficiency.
- A CTIAC system allows matching the inlet air temperature to the required turbine generating capacity, allowing 100% open inlet guide vanes and eliminating guide vane pressure loss penalties.

Summary

Combustion turbine capacity is a function of compressor mass flow rate, typically controlled by inlet air temperature. The types of cooling systems are varied, the final selection driven by the cost. Engineering economic analyses of power requirements, cooling techniques, site operational requirements, costs and climatic data are required to evaluate each CTIAC option. Details of systems, equipment, case histories, economics and project implementation can be found in the *Design Guide: Combustion Turbine Inlet Air Cooling Systems*.[5]

References

1. MacCracken, C. D. 1994. "Overview of the progress and the potential of thermal storage in off-peak turbine inlet cooling." *ASHRAE Transactions,* 100(1): 569–571.

2. Ebeling, J. A. 1994. "Combustion turbine inlet air cooling alternatives and case histories." *Proceedings of the 27th Annual Frontiers of Power Conference*.

3. EPRI. 1995. *Operating Practices Guidebook, TR-105102*.

4. *Source energy and environmental impacts of thermal energy storage*. Thermal Energy Storage Collaborative of the California Energy Commission (prepared by Tabors Caramanis & Associates). Jan. 1996.

5. Stewart, Jr., W. E. 1997. *Design Guide: Combustion Turbine Inlet Air Cooling Systems* (Final Report, RP-902), Atlanta: ASHRAE. ■