CHAPTER 17

COMBUSTION TURBINE INLET COOLING

POWER OUTPUT capacity of all combustion turbines (CTs) varies with ambient air temperature and site elevation. The rated capacities of all CTs are based on standard ambient air at 59°F, 60% rh, 14.7 psia at sea level, and zero inlet and exhaust pressure drops, as selected by the International Organization for Standardization (ISO). For all CTs, increased ambient air temperature or site elevation decreases power output; increased ambient air temperature also reduces fuel efficiency (i.e., increases the heat rate, defined as fuel energy required per unit of electric energy produced). However, the extent of the effect of these changes on output and efficiency varies with CT design. This chapter provides a detailed discussion on combustion turbine inlet cooling (CTIC). Additional information on applying CTIC to combined heat and power systems (cogeneration) is provided in Chapter 7.

There are two types of CTs: aeroderivative and industrial/frame. Figures 1 and 2 show typical effects of ambient air temperature on power output and heat rate, respectively, for these types of turbines. The actual performance of a specific CT at different inlet air temperatures depends on its design. Figures 1 and 2 show that aeroderivative CTs are more sensitive to ambient air temperature than are industrial/frame CTs. Figure 1 (Punwani and Hurlbert 2005) shows that, for a typical aeroderivative CT, an increase in inlet air temperature from 59 to 100°F on a hot summer day decreases power output to about 81% of its rated capacity: a loss of 19% of the rated capacity. Figure 2 (Punwani 2003) shows that, for the same change in ambient air temperature, the heat rate of a typical aeroderivative CT increases (i.e., fuel efficiency decreases) by about 4% of the rated heat rate at ISO conditions. Increasingly, industrial/frame CTs are using aeroderivative technology to improve performance; thus, their performance curves are moving toward those of the classic aeroderivative CT.

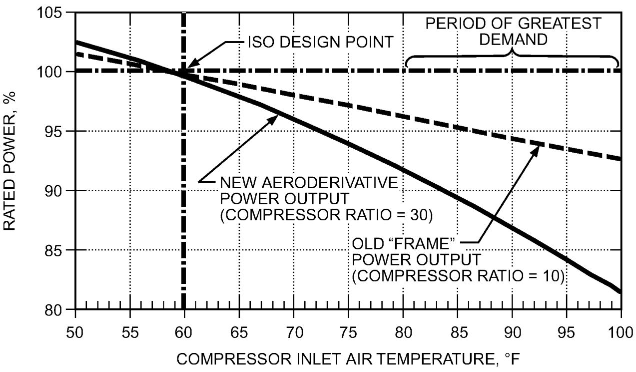

Fig. 1 Effect of Ambient Temperature on CT Output
(Punwani and Hurlbert 2005)

In cogeneration and combined-cycle systems that use thermal energy in CT exhaust gases for steam generation, heating, cooling, or more power generation, increases in ambient air temperature also reduce the total thermal energy available for these applications, as shown in Figure 3 (Orlando 1996).

CTs, in simple- and combined-cycle systems are particularly qualified to meet peak electricity demand because of their ability to start and stop more quickly than steam-turbine based thermal power generation systems using coal, oil or gas, and nuclear plants. For fossil fuel power generation, combined-cycle systems are the most fuel-efficient (lowest heat rate of typically 7000 Btu/kWh) and

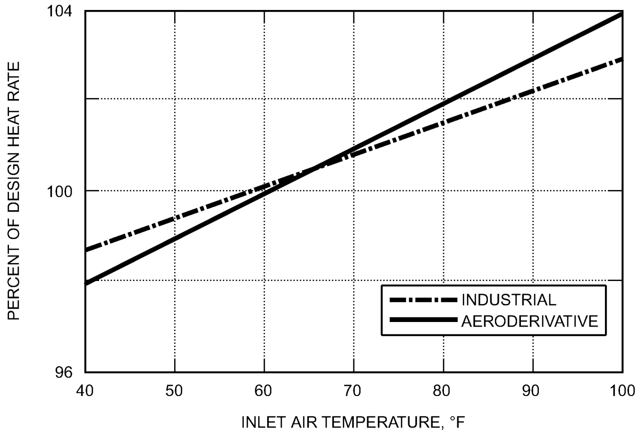

Fig. 2 Effect of Ambient Temperature on CT Heat Rate
(Punwani 2003)

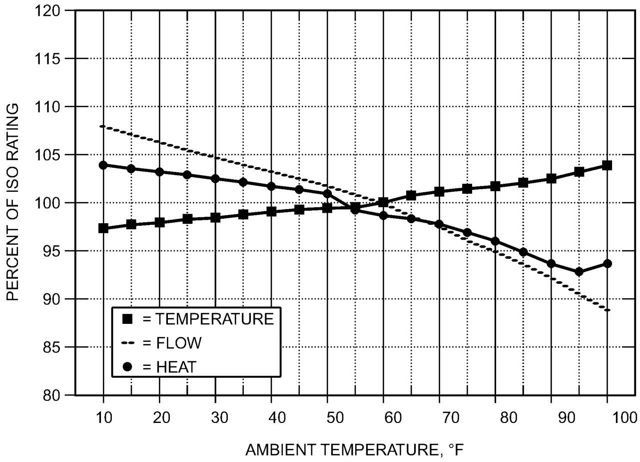

Fig. 3 Effects of Ambient Temperature on Thermal Energy, Mass Flow Rate and Temperature of CT Exhaust Gases
(Orlando 1996)

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steam-turbine-based systems are the least efficient (highest heat rate range between 12,000 to 20,000 Btu/kWh, depending on turbine age). A typical heat rate for a simple-cycle system is about 10,000 Btu/kWh. Therefore, to minimize the fuel cost for power generation, the preferred order of dispatching power to meet the market demand is to operate combined-cycle systems first, simple-cycle systems next, and steam turbines as the last resort.

Electric power demand is generally high when ambient temperatures are high. An example of an hourly profile of ambient temperature, system load, and CT output is shown in Figure 4 (Punwani and Hurlbert 2005).

When high ambient temperatures drive up power demand, the use of less efficient (high-fuel-cost) generation plants is required and that drives up the market price of electric energy. Figure 5 (Hilberg 2006) shows the hourly load profile in one of the US reliability regions for a single day in the summer. Although the peak electricity demand increases by 80%, the peak power price increases by over 400%. Figures 4 and 5 show that power output capacity decreases just when it is most needed, and when power is also most valuable.

The trends shown in Figures 4 and 5 are not unique to the United States. The Middle East is seeing much higher growth rates in power demand, and that demand is also directly linked to hot weather power usage. In some countries in the Middle East, over 40% of power usage is linked to air conditioning.

CTIC is used by thousands of CT-based power plants to overcome the ill effects of increased ambient temperature on CT performance.

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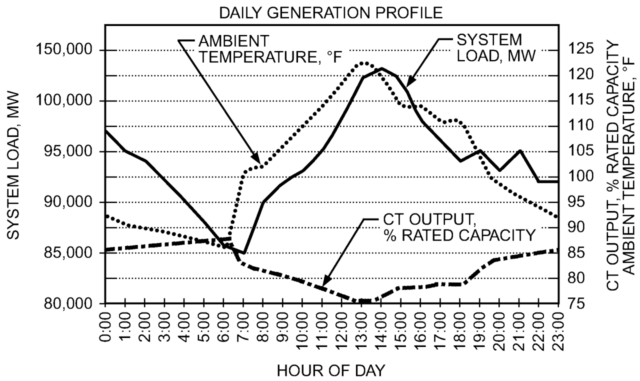

Fig. 4 Typical Hourly Power Demand Profile
(Punwani and Hurlbert 2005)

It can provide economic and environmental benefits for plant owners, ratepayers, and the general public.

ADVANTAGES

CTIC offers economic as well as environmental benefits.

Economic Benefits

- Maximizes power output when most needed and most valuable
- Reduces capital cost ($/kW) for the incremental capacity
- Increases CT fuel efficiency (lowers heat rate)
- Minimizes use of less efficient steam-turbine-based systems, thus helping to minimize increase in rates to electricity users

Environmental Benefits

- Allows minimum use of inefficient and polluting power plants by allowing maximum use of efficient and cleaner CT plants
  - Conserves natural fuel resources
  - Reduces emissions of pollutants (SO_x, NO_x, particulates, and hydrocarbons)
  - Reduces emissions of global warming/climate change gas (CO_2)
- Minimizes/eliminates new power plant siting issues

Emissions reductions from CTIC result from its displacement of the very-high-heat-rate steam turbine peaker power plants (consuming as much as 20,000 Btu/kWh operating on boilers and steam turbines), as shown in an example in Table 1.

DISADVANTAGES

- Permanently higher CT inlet pressure drop that results in a small drop in the CT output capacity even when CTIC is not being used (magnitude of pressure drop varies with CTIC technology)
- Additional maintenance cost for CTIC equipment

DEFINITION AND THEORY

A schematic flow diagram of a combustion turbine (CT) system is shown in Figure 6.

Power output of a CT is directly proportional to and limited by the mass flow rate of the compressed air available to it from the air compressor that provides high-pressure air to the combustion chamber of the CT system. An air compressor has a fixed capacity for handling a volumetric flow rate of air for a given rotational speed of

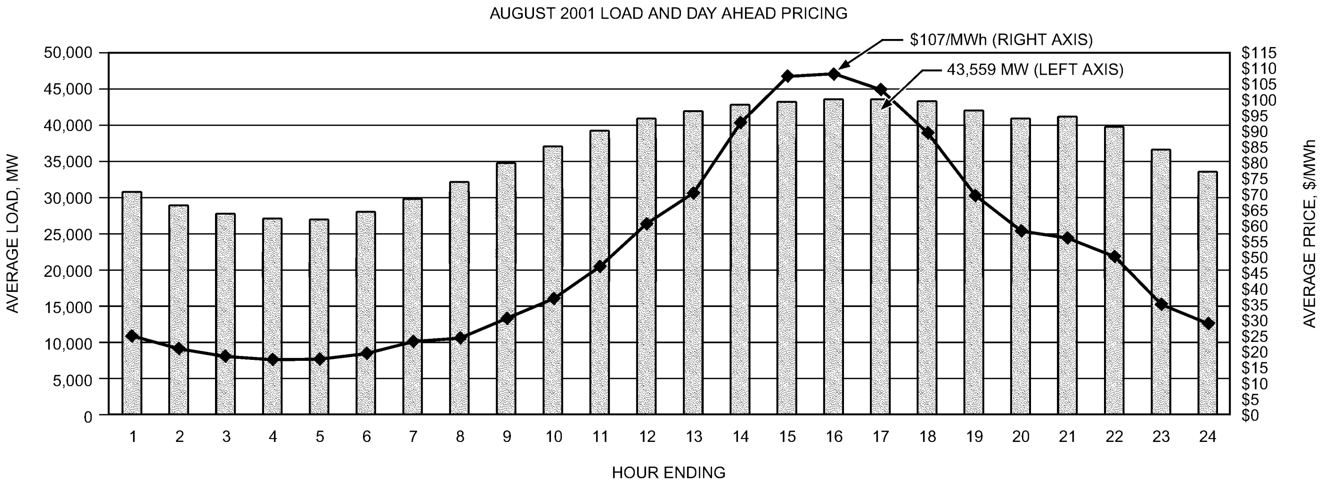

Fig. 5 Example of Daily System Load and Electric Energy Pricing Profiles
(Hilberg 2006)

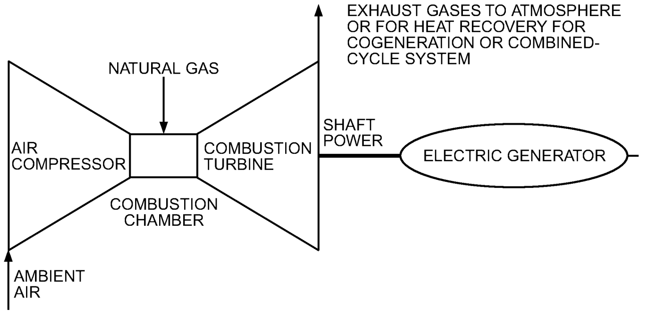

Fig. 6 Schematic Flow Diagram of Typical Combustion Turbine System

Table 1 Examples of Emissions from Typical Combined-Cycle, Simple-Cycle, and Steam Turbine Systems

	TIC Candidates		Existing Older Plants
Unit Type	**Combined-Cycle CT**	**Simple-Cycle CT**	**Boiler + Steam Turbine**
Prime mover	Frame CT-STG	Frame CT	Condensing STG
Fuel	Gas	Gas	No. 6 oil
Fuel sulfur, % weight	0	0	0.01
Plant age, yr	<5	<5	>30
Heat rate, Btu/kWh	7000	10,750	13,000
NO_x control	DLN-SCR	DLN	LNB with FRG
NO_x target, ppm	3	9	N/A
NO_x, lb/10^6 Btu	0.0114	0.0341	0.3
SO_2, lb/10^6 Btu	0	0	1.02
Incremental capacity, MW	100	100	100
Hours of operation	400	400	400
Fuel, 10^6 Btu	280,000	430,000	520,000
CO_2 emissions, tons	16,275	24,993	44,730
NO_x emissions, tons	1.595	7.3315	78
SO_x emissions, tons	0	0	265.2

LNB = low NO_x burners
DLN = dry low NO_x
FGR = fuel gas recirculation
SCR = selective catalytic NO_x reduction

the compressor. Even though the volumetric capacity of a compressor remains constant, the mass flow rate of air it delivers to the CT changes with ambient air temperature. The mass flow rate of air decreases as the air density decreases with increasing ambient temperature. CTIC reduces the inlet air temperature, resulting in increases in air density mass flow rate and power output. For more details, consult Stewart (1999).

SYSTEM TYPES

Many technologies are commercially available for CTIC, but the overall approaches can be divided into three major groups:

- Evaporative systems
- Chiller systems
- Liquefied natural gas (LNG) vaporization systems

Each approach has advantages and disadvantages; for more information, see Stewart (1999).

Evaporative Systems

Evaporative cooling systems rely on cooling produced by evaporation of water added into the inlet air. An ideal evaporative cooling process occurs at a constant wet-bulb temperature and cools the air to a higher relative humidity (i.e., water vapor content increases). When the warm ambient inlet air comes in contact with the added water, it transfers some of its heat to the liquid water and evaporates some of the water. The process of heat transfer from inlet air to water cools the inlet air. Water added in the evaporative systems also acts as an air washer by cleaning the inlet air stream of airborne particulates and soluble gases, which could be a significant benefit to downstream filter elements. Studies show that evaporative cooling also reduces NO_x emissions because of the increase in moisture added to the air. The psychrometry of CTIC using evaporative systems has been described in detail by Stewart (1999).

Evaporative systems can cool the inlet air up to 98% of the difference between the ambient dry-bulb and wet-bulb temperatures. Therefore, the most cooling can be achieved during hot and/or dry weather. Design and hourly wet-bulb temperatures for many locations can be found in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals* and the *Weather Year for Energy Calculations 2 (WYEC2) Data and Toolkit CD* (ASHRAE 1997). This information is useful in evaluating the cooling potential for locations in many climates.

Evaporative systems have the lowest capital costs among CTIC systems, and are the most common type in use. Their primary disadvantage is that the extent of cooling produced is limited by the wet-bulb temperature (and thus, cooling is weather dependent). In arid climates, these systems consume large quantities of water (e.g., about 5 gal/h to cool 10,000 cfm of air by 20°F), which comprises the major component of the system operating cost.

Two primary system types are commercially used for evaporative cooling: wetted media and fogging.

Wetted Media. As the first approach adopted for CTIC, these systems have a long history of success in a wide range of operating climates. Inlet air is exposed to a thin film of water on the extended surface of honeycomb-like wetted media. Water used for wetting may or may not require treatment, depending on its quality and the medium manufacturer's specifications.

Typical pressure drop across the wetted media is about 0.3 in. of water. The higher the degree of saturation required, the more media required and higher the pressure drop. A wetted-media system requires proper control of the chemistry of recirculating water (e.g. contaminant absorption) and monitoring of media degradation (Graef 2004). The media may need to be replaced every 5 to 10 years, depending on water quality, air quality, and hours of operation.

Fogging. This approach adds moisture to the inlet air by spraying very fine droplets of water. High-pressure fogging systems can be designed to produce droplets of variable sizes, depending on the desired evaporation time and ambient conditions. The water droplet size is generally less than 40 µm, and averages about 20 µm. Fogging systems typically require higher-quality water than wetted-media systems do. Generally, reverse-osmosis or demineralized water is used to ensure cleanliness throughout the system. Typical pressure drop across the fogging section is about 0.1 in. of water. Fogging nozzles may need to be replaced every 5 to 10 years because of erosion. The high-pressure pumps require servicing at least annually.

A fogging system that sprays more water than could evaporate before the inlet air enters the compressor is known as a **wet compression**, **overspray**, **high-fogging**, or **over-fogging system** (Jolly 2005; Kraft 2004; Schwieger 2004). Water in excess of that required by fogging does not further reduce inlet air temperature. It is ingested into the compressor section of the CT, and provides a threefold effect for the system:

- It ensures inlet air achieves maximum evaporative cooling.
- The additional water evaporates in the compression stages of the compressor, allowing the compressor to be cooler and require less work for air compression.
- The excess water increases the total mass flow rate of gases entering the CT and helps increase power output beyond that possible with fogging alone.

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There is debate in the industry whether wet compression is truly a CTIC technology; accordingly, this chapter addresses only the inlet fogging contribution of wet compression technology.

Chiller Systems

Chiller systems cool inlet air by exchange of heat through indirect or direct contact between warm ambient inlet air and a cold fluid produced by chillers. In **indirect heat exchange systems**, chilled fluid flows inside a coil while the inlet air flows across the coil face. Typical inlet-air-side pressure drop across the heat exchange coil is about 1 in. of water. The water vapor content (humidity ratio) of the inlet air remains constant as its dry-bulb temperature decreases. Ammonia is most commonly used chilled fluid in direct refrigerant applications; for indirect-contact heat exchange systems, the preferred chilled fluid is often water, though water/glycol, HFCs, HCFCs, and other aqueous fluids are also used.

Recently, a **direct heat exchange system** (also known as a **bulk air cooler**) has been introduced. It uses wetted media in combination with chillers, and allows the flexibility of using wetted media either with ambient temperature water or with chilled water, depending on the desired power output capacity. A direct-contact heat exchanger operating without chilling the added water performs just as a wetted-media evaporative system does, except that the pressure drop is about 0.8 in. of water. Stewart (1999) describes the psychrometry of CTIC for chilled-fluid systems in detail.

The primary advantage of chiller systems is that they can cool inlet air to much lower temperatures (thus enhancing power output capacity more than evaporative cooling systems can), and can maintain any desired inlet air temperature down to 42°F, independent of ambient dry-bulb and wet-bulb temperature. Additional inlet air cooling of up to 8 to 10°F may occur in the bell-mouth section of the air compressor inlet housing, depending on housing design; during hot and humid weather, this additional temperature drop may be enough to cause the temperature of moisture-saturated air to fall below 32°F and form ice crystals, which could damage compressor blades. If, however, the ambient air is very dry, inlet air could be cooled below 42°F (Stewart 2001).

The primary disadvantages of chiller systems are that their installed costs and inlet air pressure drops (which lead to power loss even when CTIC is not being used) are much higher than those for evaporative systems. Chiller systems could be air or water cooled; water-cooled systems are the most common. Most water-cooled chiller systems require cooling towers, although some directly use seawater. Systems that use cooling towers require makeup water, which may require treatment, although usually less than is required by evaporative systems. Makeup water required for cooling towers is about 20 to 30 gpm per 1000 ton of chiller capacity. During hot and humid weather conditions, most chiller systems produce saturated air and require mist eliminators downstream of the cooling to minimize the potential for water carryover from the cooling coil. It is also common to collect the condensate that forms on the inlet air coils; this can offset a substantial portion of the cooling tower makeup water requirements.

Chiller systems can use mechanical and/or absorption chillers, with or without thermal energy storage (TES).

Mechanical chillers used in CTIC systems could be centrifugal, screw, or reciprocating, and could driven by electric motors, steam turbines, or engines. These chillers can use CFCs, HCFCs, or ammonia as a refrigerant and can cool the inlet air to 42°F (or below, if desired) without the risk of forming ice crystals. Installed cost of motor-driven mechanical chillers is lower than that for any other chiller, but their parasitic loads are the highest: 0.6 to 0.8 kW per ton of refrigeration. Mechanical chillers driven by steam turbines or engines have lower parasitic electrical loads (0.03 kW/ton), but require fuel or heat inputs and have a higher installed cost. Mechanical chillers are more commonly used for CTIC than are absorption chillers.

Absorption chillers require thermal energy from steam, hot water, hot exhaust gases, or natural gas as the primary source of energy, and need much less electric energy than mechanical chillers. If water is used as the refrigerant, as is most common for CTIC, inlet air can be cooled to about 50°F; if ammonia is the refrigerant, air temperatures will be similar to those available using mechanical chillers.

Absorption chillers can be single or double effect. Single-effect absorption chillers use hot water or 15 psig steam (18 lb/ h·ton), whereas double-effect chillers require less steam (10 lb/ h·ton) but need it at higher pressure (typically 115 psig). The advantage of an absorption chiller system is that it has much less parasitic electric load (typically, 0.03 kW/ton), but its capital cost is higher than that for mechanical chiller systems. Their main successful application is in power plants where excess waste thermal energy is available, and where use of this energy saves higher-value electric energy.

Thermal energy storage (TES) is used in chilled-fluid systems to increase the available net power output capacity during on-peak periods. It is typically used when only a small number of hours per day require inlet air cooling, or when power enhancement is highly valued. TES systems incorporate tanks that store chilled fluid or ice, which is produced by chillers or refrigeration systems during off-peak periods, when the market value of electric energy is low. The stored chilled water or ice is used to cool the inlet air during on-peak periods, when the value of electric energy is high. The primary advantage of a TES system is that it can reduce total system capital cost by reducing chiller capacity requirements from that required to match the instantaneous on-peak demand for cooling. It also increases on-peak capacity and revenues for the power plant, because little or no electric energy is required to operate the chillers during the high-demand, high-value, on-peak periods. The disadvantage of a TES system is that it requires a larger site footprint for the TES tank.

There are two types of TES systems: full and partial shift. In **full-shift systems**, chillers are not operated during on-peak periods; all the required cooling is achieved by using the chilled fluid or ice from the TES tank. In **partial-shift systems**, the down-sized chiller system also runs during on-peak periods to complement the cooling capacity available from the stored chilled fluid or ice.

Several publications compare the performance and economics of TES options for CTIC (Andrepont 1994) or provide methodology for their analysis (Andrepont and Pasteris 2003) and case studies (Liebendorfer and Andrepont 2005). A database of TES-CTIC applications has been developed and analyzed, illustrating the trends in TES-CTIC technology, capacity, and geographic locales, as well as demonstrating the performance and economic advantages of combining TES with TIC in many applications (Andrepont 2005; Dec and Andrepont 2006).

LNG Vaporization Systems

These systems are useful for power plants located near a liquefied natural gas (LNG) import facility. In supplying natural gas for pipelines, power plants, or other applications, LNG must be vaporized by some heat source. For applications in CTIC, the inlet air is used as such a heat source. Cho et al. (2003) and Punwani and Pasteris (2004) give examples of LNG vaporization systems.

CALCULATION OF POWER CAPACITY ENHANCEMENT AND ECONOMICS

A CTIC system's power capacity enhancement and economics depends on several parameters, including the following:

- CT design and characteristics
    - CT heat rate versus compressor inlet air temperature
    - CT power output versus compressor inlet air temperature
    - CT airflow (not an independent variable; dependent on compressor inlet air temperature)

- CTIC design characteristics
    - Parasitic load
    - Pressure drop across the component inserted upstream of the compressor (insertion loss)
    - Water usage
- Hourly weather data (dry-bulb and coincident wet-bulb temperatures) for the geographic location of the CT
- Selected ambient design conditions
- Selected cooled air temperature upstream of compressor
- Cost of fuel
- Cost of water
- Power demand profile
- Hourly market value of electric energy
- Hourly market value of plant capacity

Preliminary estimates of net capacity enhancement by CTIC and the associated costs can be made by the following calculation procedure, which is based on several rules of thumb. More accurate calculations can require sophisticated combustion turbine models and site-specific cost analyses.

Cooling. Cooling achieved is easily calculated for all of the systems.

Media and fogger evaporative coolers cool a percentage of the difference between wet-bulb (WB) and dry-bulb (DB) temperatures:

$$\text{Degrees of cooling} = \text{Cooling efficiency} \times (\text{DB} - \text{WB})$$

Chillers are sized to cool to the selected design temperature:

$$\text{CCL} = AF_m(H_a - H_c)/12{,}000$$

where

CCL = Chiller cooling load, tons
AF_m = Mass flow rate of cooled air, lb/h
H_a = Enthalpy of ambient air, Btu/lb
H_c = Enthalpy of cooled air, Btu/lb
12,000 = Ton of cooling, Btu/h

Parasitic Loss. Parasitic loss is the power required to run the CTIC system.

Media evaporative coolers consume the same amount of power any time the pump is energized, regardless of cooling produced. The total power required varies depending on pumping head, pressure drop of valves, and other restrictions, but a reasonable estimate is 0.02 W/cfm.

Fogging systems power consumption is a function of the amount of water injected into the air, and water pressure. For a water pressure of 3000 psi, the parasitic loss is approximately 2 kW/gpm).

Chillers consume power based on the cooling load and condenser temperature.

$$\text{Chiller parasitic load, kW} = 0.7 \times \text{CCL}$$

The cooling load of the cooling tower (CTL), in tons, is 125% of the chiller load. Estimate the water flow rate capacity (CTC) of the cooling tower at a rate of 3 gpm × CTL. The power of the pump and fan is estimated by the following equation:

$$\text{Tower parasitic load, kW} = 6 \times \text{CTC}/(38 \times 1.341)$$

For air-cooled chillers, power usage is greater than for water-cooled chillers, and is a function of the dry-bulb (rather than the wet-bulb) ambient air temperature.

For chillers integrated with TES, most or all of the chiller parasitic load (excluding some water pumps) can be eliminated during peak periods of CTIC operation, with the chiller operating (and the associated parasitic load) during off-peak times of lower power demand and lower power value.

Insertion Loss. All CTs have an insertion loss, which reduces the turbine's power output by approximately 0.25% per in. of water of pressure differential across the inserted component. The pressure differential for the evaporative cooler when no water is being injected (cooler not in operation) is about half as much as when it is running. Insertion loss on a cooling coil also decreases when it is not running or there is no condensate on the coil.

Net and Gross Power Increase. Figure 1 shows typical power degradation caused by increased ambient temperature. For a new aeroderivative CT, power can be lost or restored at an estimated rate of 0.44% per °F of temperature change. Using these numbers, the power output of the CT can be estimated with and without CTIC. The gross power increase is the difference between these two values. The net power increase is the gross increase less all parasitic loads.

Fuel Usage. Figure 2 shows the change in heat rate with increase in inlet air temperature. The curve for the industrial turbine can be estimated to be 0.08% per °F. Fuel usage of the CT at ISO standard conditions ranges between 8 and 12,000 Btu/kWh.

Fuel usage must be calculated for the turbine with and without cooling. Fuel consumption is greater (but more efficient) when the air has been cooled, and the cost of this additional fuel should be deducted from the gross increase in revenue.

Water Usage. Water is often a precious commodity at industrial sites. Usage can be estimated as follows.

For media and fogging evaporative coolers, water usage is a function of the amount of cooling and the airflow:

$$\text{Water usage, gph} = \frac{1.2 \times \Delta t \times AF_v}{10{,}000}$$

where

Δt = Degrees of cooling, °F
AF_v = Volumetric airflow rate, cfm

Water evaporation can also be calculated by multiplying the difference in pounds of moisture of the entering (v_1) and leaving (v_2) air times the weight per minute of airflow:

$$\text{Evaporation, gpm} = \frac{(v_2 - v_1) \times AF_m}{8.337}$$

Bleedoff from media evaporative coolers should be added to the evaporated water when calculating the cost of water. Typical bleed rates range between 10 and 50% of the evaporation rate. Foggers use high-purity water produced by reverse osmosis or demineralization; this water produces a waste stream of 10 to 30% that may need to be included in the water usage calculation.

Water-cooled chillers use water at the cooling tower. Usage is a function of the amount of cooling, and is about 0.02 to 0.03 gpm per ton of chiller capacity.

Bleedoff and drift from the cooling tower should be added to the evaporated water when refining the calculation for water cost. The bleed depends on water treatment and quality, and drift is a function of the tower's water recirculation rate. For more information, refer to Chapter 39.

In applications using cooling coils or bulk air coolers to cool the turbine inlet air stream, water may be produced by condensing (if ambient air is cooled below its dew point) and capturing moisture contained in the inlet air. This water can then be used in other locations of the power plant.

CTIC Cost. There are many variables in the cost, including turbine capacity, location, local labor rates, applicable local codes, and customer specifications.

Total installed cost of the CTIC system increases (although the cost per unit of capacity decreases) with increases in CT output and airflow rate capacities, because an increase in CT capacity increases

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the face area of the media for an evaporative cooler, and increases capacity and the heat exchange coil for the chiller system. For inlet fogging systems, increased airflow means an increase in pumping capacity and in the number of nozzles, pumps and stages. For the same reason, fogging system cost also increases proportionately with increasing differences between the wet- and dry-bulb temperatures. This can be equated to the enthalpy difference between air entering and leaving the coil. When sizing the chiller system, calculations should be based on the actual airflow of the cooled air.

The cost of chiller systems depends heavily on the cooling load for the design day, and on whether (and in what configuration) thermal energy storage (TES) is integrated with the CTIC chiller system.

Operation and Maintenance (O&M) Cost. O&M cost must also be considered, and varies considerably with the type of CTIC technology used. For an overview of O&M costs in general, see Chapter 36 of the 2007 *ASHRAE Handbook—HVAC Applications*.

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