

CHAPTER 40. COOLING TOWERS

MOST air-conditioning systems and industrial processes generate heat that must be removed and dissipated. Water is commonly used as a heat transfer medium to remove heat from refrigerant condensers or industrial process heat exchangers. In the past, this was accomplished by drawing a continuous stream of water from a utility water supply or a natural body of water, heating it as it passed through the process, and then discharging the water directly to a sewer or returning it to the body of water. Water purchased from utilities for this purpose has become prohibitively expensive because of increased water supply and disposal costs. Similarly, cooling water drawn from natural sources is relatively unavailable because the ecological disturbance caused by the increased temperature of discharge water has become unacceptable.

Air-cooled heat exchangers cool water by rejecting heat directly to the atmosphere, but the first cost and fan energy consumption of these devices are high and the plan area required is relatively large. They can economically cool water to within approximately 20°F of the ambient dry-bulb temperature; too high for the cooling water requirements of most refrigeration systems and many industrial processes.

Cooling towers overcome most of these problems and therefore are commonly used to dissipate heat from refrigeration, air-conditioning, and industrial process systems. The water consumption rate of a cooling tower system is only about 5% of that of a once-through system, making it the least expensive system to operate with purchased water supplies. Additionally, the amount of heated water discharged (**blowdown**) is very small, so the ecological effect is greatly reduced. Lastly, cooling towers can cool water to within 4 to 5°F of the ambient wet-bulb temperature, which is always lower than the ambient dry-bulb, or approximately 35°F lower than can air-cooled systems of reasonable size (in the 250 to 500 ton range). This lower temperature improves the efficiency of the overall system, thereby reducing energy use significantly and increasing process output.

1. PRINCIPLE OF OPERATION

A cooling tower cools water by a combination of heat and mass transfer. Water to be cooled is distributed in the tower by spray nozzles, splash bars, or film-type fill, which exposes a very large water surface area to atmospheric air. Atmospheric air is circulated by (1) fans, (2) convective currents, (3) natural wind currents, or (4) induction effect from sprays. A portion of the water absorbs heat to change from a liquid to a vapor at constant pressure. This heat of vaporization at atmospheric pressure is transferred from the water remaining in the liquid state into the airstream.

Figure 1 shows the temperature relationship between water and air as they pass through a counterflow cooling tower. The curves indicate the drop in water temperature (A to B) and the rise in the air wet-bulb temperature (C to D) in their respective passages through the tower. The temperature difference between the water entering and leaving the cooling tower (A minus B) is the range. For a steady-state system, the range is the same as the water temperature rise through the load heat exchanger, provided the flow rate through the cooling tower and heat exchanger are the same. Accordingly, the range is determined by the heat load and water flow rate, not by the size or thermal capability of the cooling tower.

The difference between the leaving water temperature and entering air wet-bulb temperature (B minus C) in Figure 1 is the approach to the wet-bulb or simply the approach of the cooling tower. The approach is a function of cooling tower capability. A larger cooling tower produces a closer approach (colder leaving water) for a given heat load, flow rate, and entering air condition. Therefore, the amount of heat transferred to the atmosphere by the cooling tower is always equal to the heat load imposed on the tower, whereas the temperature level at which the heat is transferred is determined by the thermal capability of the cooling tower and the entering air wet-bulb temperature.

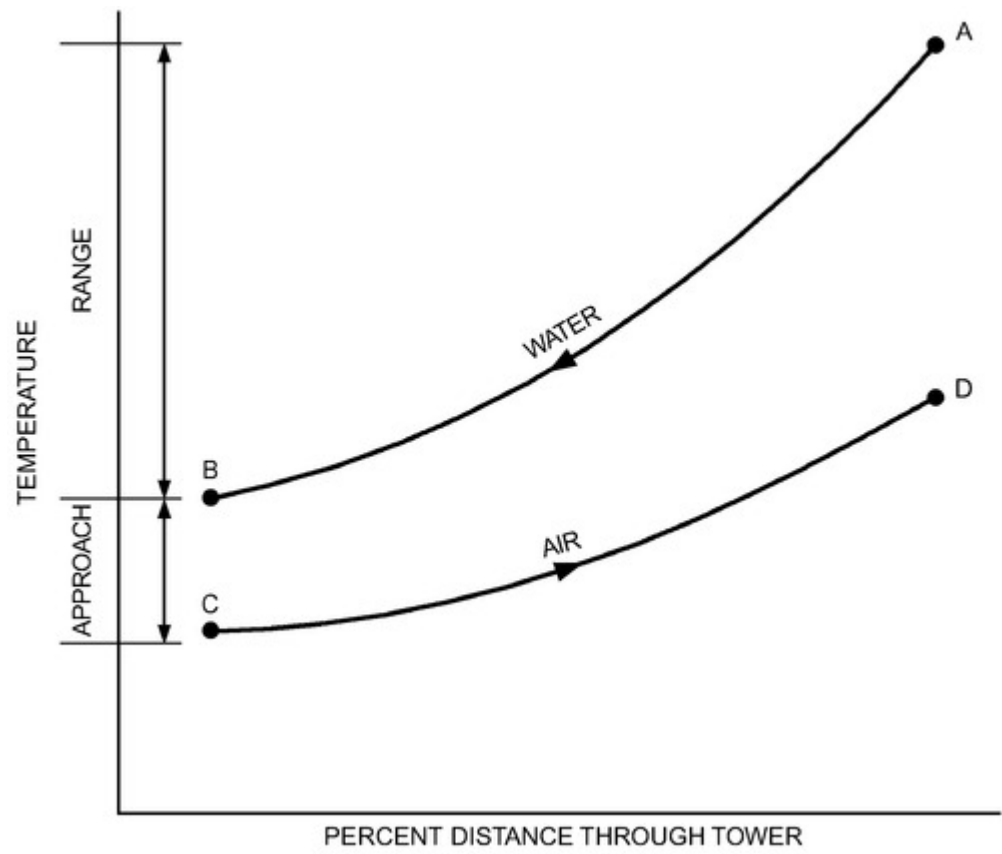


Figure 1. Temperature Relationship Between Water and Air in Counterflow Cooling Tower

Thermal performance of a cooling tower depends mainly on the entering air wet-bulb temperature. The entering air dry-bulb temperature and relative humidity, taken independently, have an insignificant effect on thermal performance of mechanical-draft cooling towers, but do affect the rate of water evaporation in the cooling tower. A psychrometric analysis of the air passing through a cooling tower illustrates this effect (Figure 2). Air enters at the ambient condition point A, absorbs heat and mass (moisture) from the water, and exits at point B in a saturated condition (at very light loads, the discharge air may not be fully saturated). The amount of heat transferred from the water to the air is proportional to the difference in enthalpy of the air between the entering and leaving conditions ($h_B - h_A$). Because lines of constant enthalpy correspond almost exactly to lines of constant wet-bulb temperature, the change in enthalpy of the air may be determined by the change in wet-bulb temperature of the air.

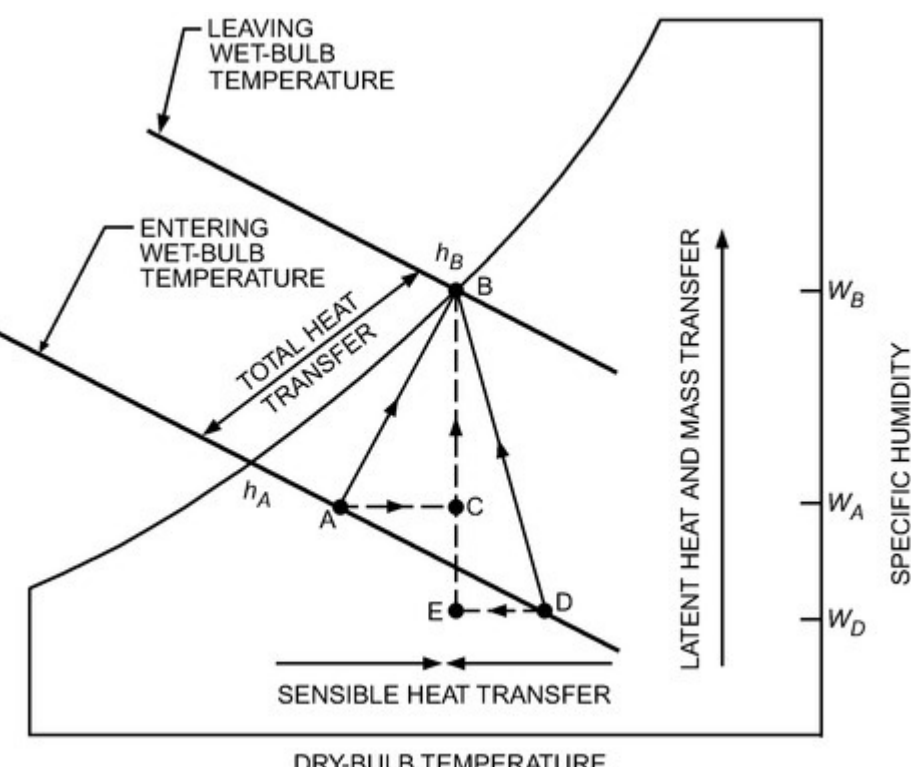


Figure 2. Psychrometric Analysis of Air Passing Through Cooling Tower

Air heating (vector AB in Figure 2) may be separated into component AC, which represents the sensible portion of the heat absorbed by the air as the water is cooled, and component CB, which represents the latent portion. If the entering air condition is changed to point D at the same wet-bulb temperature but at a higher dry-bulb temperature, the total heat transfer (vector DB) remains the same, but the sensible and latent components change dramatically. DE represents sensible cooling of air, whereas EB represents latent heating as water gives up heat and mass to the air. Thus, for the same water-cooling load, the ratio of latent to sensible heat transfer can vary significantly.

The ratio of latent to sensible heat is important in analyzing water usage of a cooling tower. Mass transfer (evaporation) occurs only in the latent portion of heat transfer and is proportional to the change in specific humidity. Because the entering air dry-bulb temperature or relative humidity affects the latent to sensible heat transfer ratio, it also affects the rate of evaporation. In Figure 2, the rate of evaporation in case AB ($W_B - W_A$) is less than in case DB ($W_B - W_D$) because the latent heat transfer (mass transfer) represents a smaller portion of the total.

The evaporation rate at typical design conditions is approximately 1% of the water flow rate for each 12.5°F of water temperature range; however, the average evaporation rate over the operating season is less than the design rate because the sensible component of total heat transfer increases as entering air temperature decreases. The evaporation rate is also directly proportional to the load; this must be taken into account when estimating annual water usage.

In addition to water loss from evaporation, losses also occur because of liquid carryover into the discharge airstream and blowdown to maintain acceptable water quality. Both of these factors are addressed later in this chapter.

2. DESIGN CONDITIONS

The thermal capability of any cooling tower may be defined by the following parameters:

- Entering and leaving water temperatures
- Entering air wet-bulb (and sometimes dry-bulb) temperatures
- Water flow rate

The entering air dry-bulb temperature affects the amount of water evaporated from any evaporative cooling tower. It also affects airflow through hyperbolic towers and directly establishes thermal capability in any indirect contact cooling tower component operating in a dry mode. Variations in tower performance associated with changes in the remaining parameters are covered in the section on Performance Curves.

The thermal capability of a cooling tower used for air conditioning is often expressed in nominal cooling tower tons. A nominal cooling tower ton is defined as cooling 3 gpm of water from 95°F to 85°F at a 78°F entering air wet-bulb temperature. At these conditions, the cooling tower rejects 15,000 Btu/h per nominal cooling tower ton. The historical derivation of this 15,000 Btu/h cooling tower ton, as compared to the 12,000 Btu/h evaporator ton, is based on the assumption that at typical air-conditioning conditions, for every 12,000 Btu/h of heat picked up in the evaporator, the cooling tower must dissipate an additional 3000 Btu/h of compressor heat. Newer, high-efficiency compressor systems have significantly reduced the amount of compressor heat generated. For specific applications, nominal capacity ratings are not used, and the thermal performance capability of the cooling tower is usually expressed as a water flow rate at specific operating temperature conditions (entering water temperature, leaving water temperature, entering air wet-bulb temperature).

3. TYPES OF COOLING TOWERS

Two basic types of evaporative cooling devices are used. The **direct-contact or open cooling tower** (Figure 3), exposes water directly to the cooling atmosphere, thereby transferring the source heat load directly to the air. A **closed-circuit cooling tower**, involves **indirect contact** between heated fluid and atmosphere (Figure 4), essentially combining a heat exchanger and cooling tower into one relatively compact device.

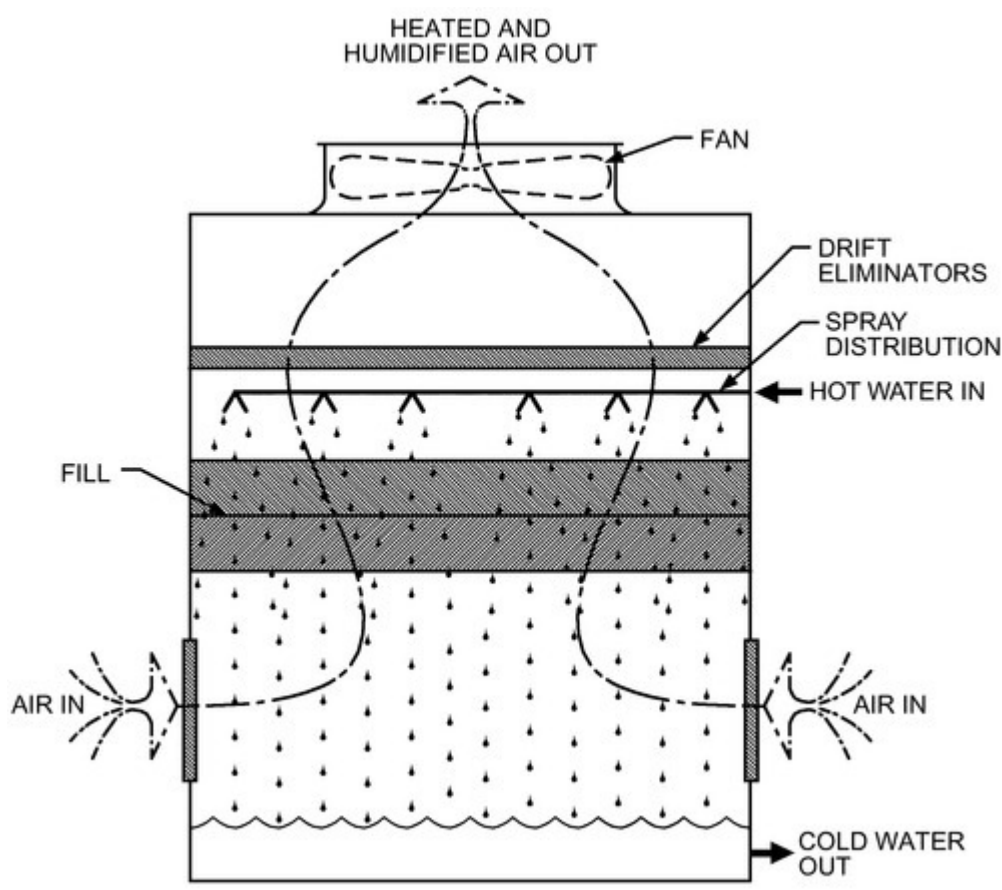


Figure 3. Direct-Contact or Open Evaporative Cooling Tower

Of the direct-contact devices, the most rudimentary is a spray-filled cooling tower that exposes water to the air without any heat transfer medium or fill. In this device, the amount of water surface exposed to the air depends on the spray efficiency, and the time of contact depends on the elevation and pressure of the water distribution system.

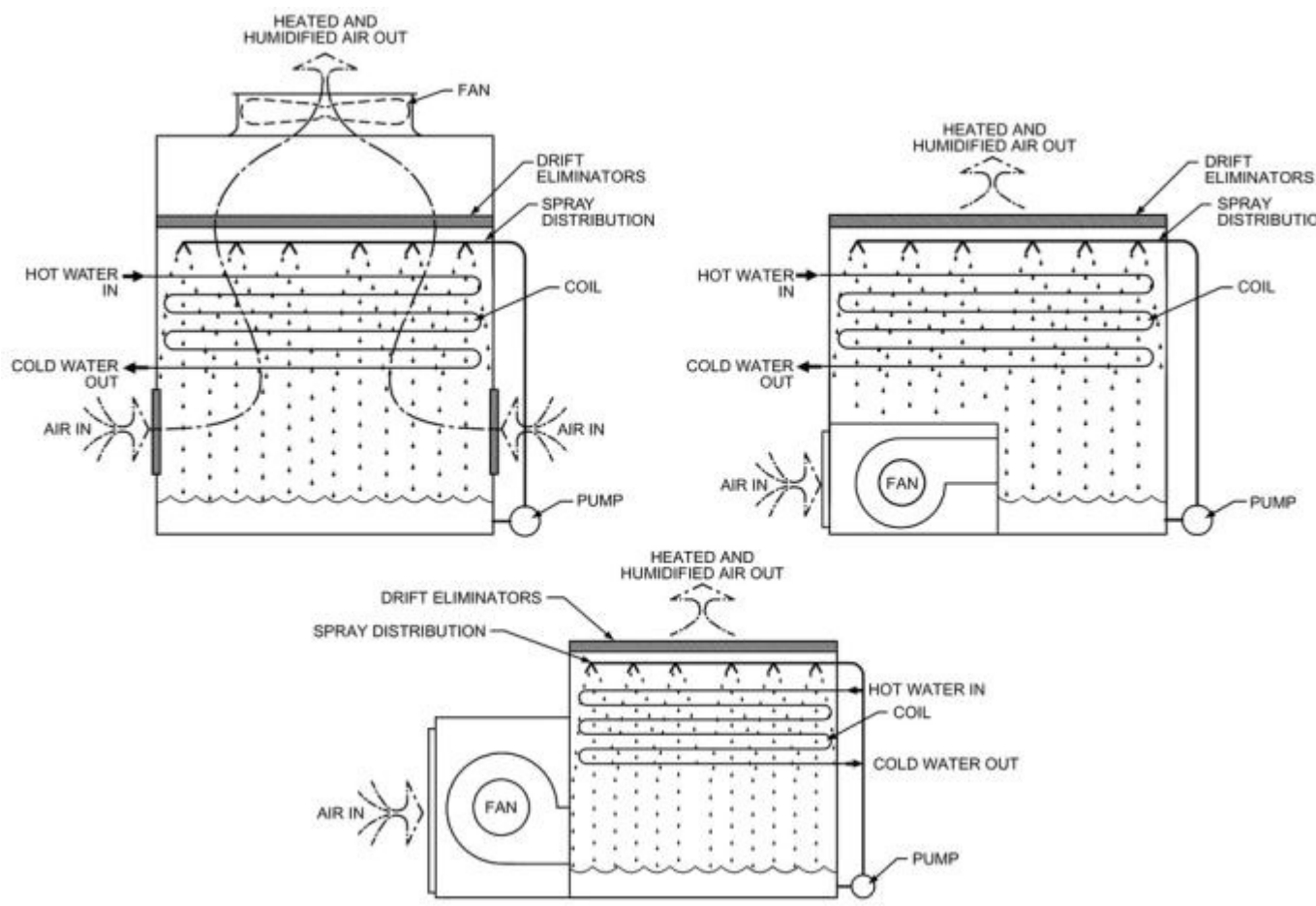


Figure 4. Indirect-Contact or Closed-Circuit Evaporative Cooling Towers

To increase contact surfaces as well as time of exposure, a heat transfer medium, or fill, is installed below the water distribution system, in the path of the air. The two types of fill in use are splash-type and film-type (Figure 5A). Splash-type fill maximizes contact area and time by forcing the water to cascade through successive elevations of splash bars arranged in staggered rows. Film-type fill achieves the same effect by causing the water to flow in a thin layer over closely spaced sheets, principally polyvinyl chloride (PVC), that are arranged vertically.

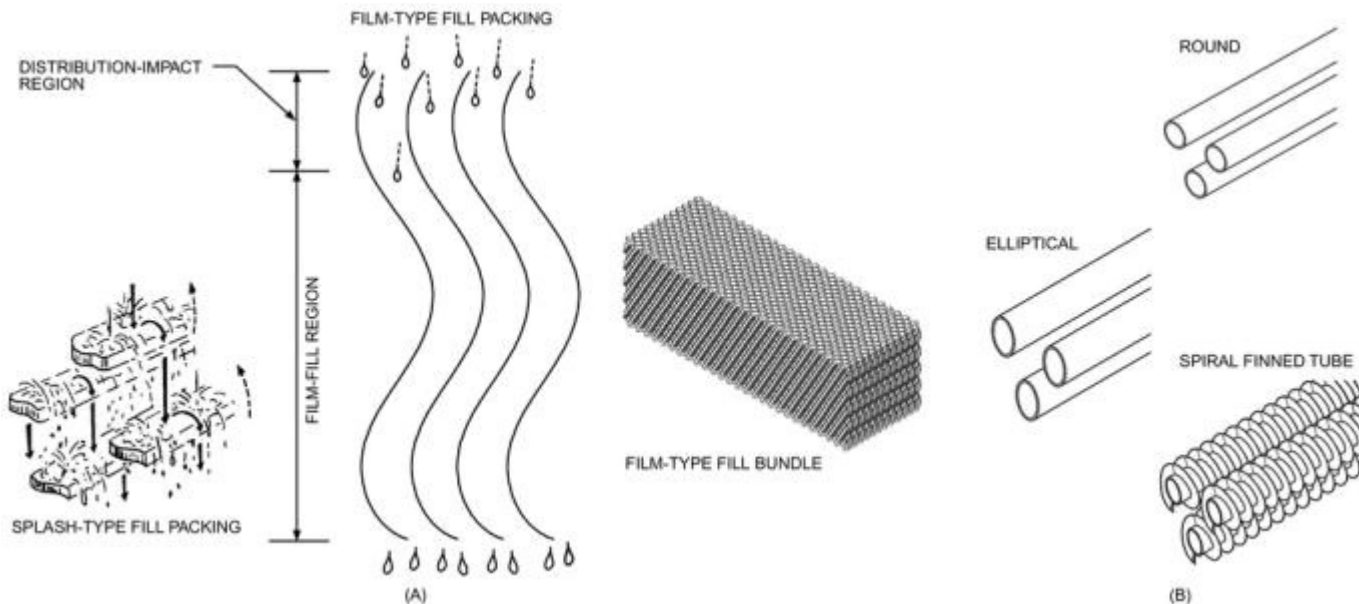


Figure 5. Types of (A) Fill and (B) Coils

Either type of fill can be used in counterflow and cross-flow cooling towers. For thermal performance levels typically encountered in air conditioning and refrigeration, a tower with film-type fill is usually more compact. However, splash-type fill is less sensitive to initial air and water distribution and, along with specially configured, more widely spaced film-type fills, is preferred for applications that may be subjected to blockage by scale, silt, or biological fouling.

Indirect-contact (closed-circuit) cooling towers contain two separate fluid circuits: (1) an external circuit, in which water is exposed to the atmosphere as it cascades over the tubes of a coil bundle, and (2) an internal circuit, in which the fluid to be cooled circulates inside the tubes of the coil bundle. In operation, heat flows from the internal fluid circuit, through the tube walls of the coil, to the external water circuit and then, by heat and mass transfer, to atmospheric air. Because the internal fluid circuit never contacts the atmosphere, this unit can be used to cool fluids other than water and/or to prevent contamination of the primary cooling circuit with airborne dirt and impurities. Some closed-circuit cooling tower designs include cooling tower fill to augment heat exchange in the coil (Figure 6).

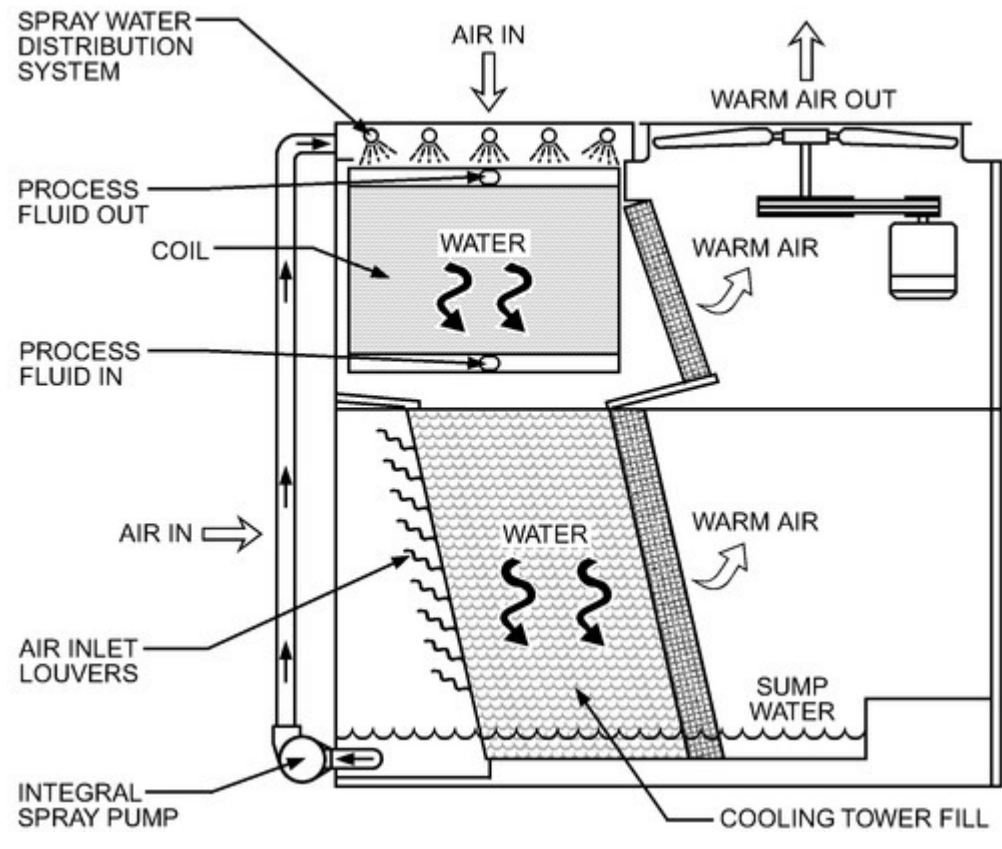


Figure 6. Combined Flow Coil/Fill Evaporative Cooling Tower

Coil Shed Cooling Towers (Mechanical Draft). Coil shed cooling towers usually consist of isolated coil sections (nonventilated) located beneath a conventional cooling tower (Figure 7). Counterflow and cross-flow types are available with either forced- or induced draft fan arrangements. Redistribution water pans at the tower's base may be used to feed cooled water by gravity flow to the tubular heat exchange bundles (coils). These units are similar in function to closed-circuit fluid coolers, except that supplemental fill is always required, and the airstream is directed only through the fill regions of the cooling tower. Often, designs allow water from the fill section to impinge directly on the coil(s). These units are arranged as field-erected, multifan cell towers and are used primarily in industrial process cooling. Modular factory-assembled versions are also available.

Direct-Contact Cooling Towers

Nonmechanical-Draft Cooling Towers. Aspirated by sprays or a differential in air density, these towers do not contain fill and do not use a mechanical air-moving device. The aspirating effect of the water spray, either vertical (Figure 8) or horizontal (Figure 9), induces airflow through the cooling tower in a parallel flow pattern.

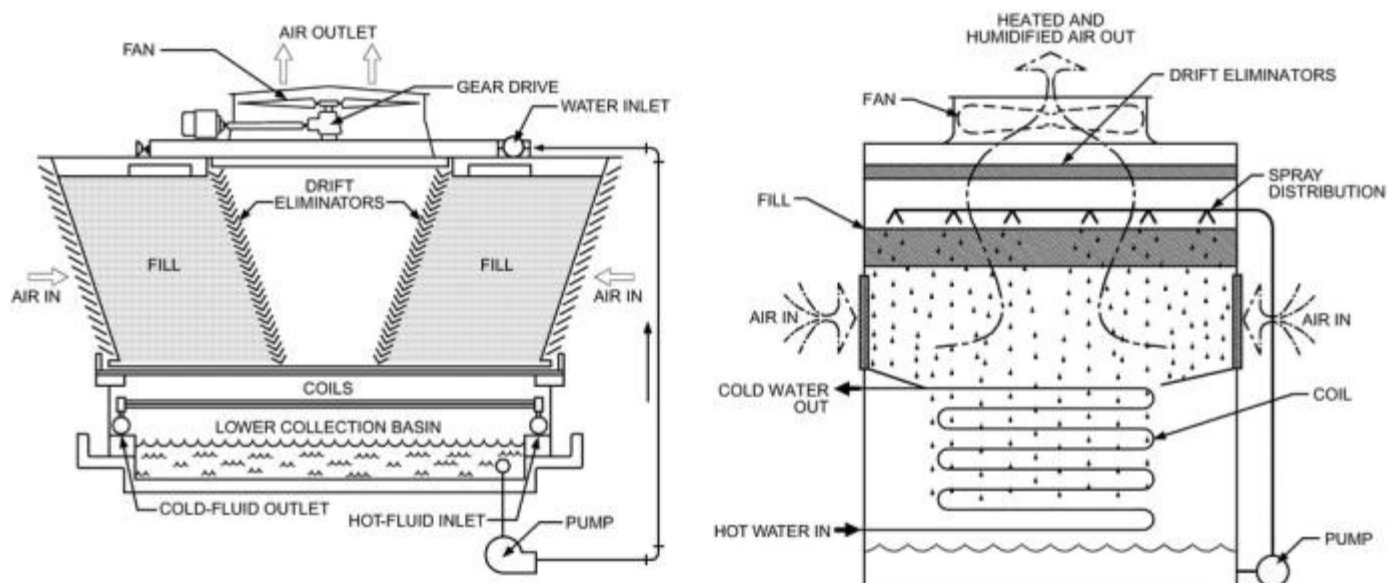


Figure 7. Coil Shed Cooling Tower

Because air velocities for the vertical spray tower (both entering and leaving) are relatively low, such cooling towers are susceptible to adverse wind effects and, therefore, are normally used to satisfy a low-cost requirement when operating temperatures are not critical to the system. Some horizontal spray cooling towers (Figure 9) use high-pressure sprays to induce large air quantities and improve air/water contact. Multispeed or staged pumping systems are normally recommended to reduce energy use in periods of reduced load and ambient conditions.

Chimney (hyperbolic) towers have been used primarily for large power installations, but may be of generic interest (Figure 10). The heat transfer mode may be counterflow, cross-flow, or parallel flow. Air is induced through the cooling tower by the air density differentials that exist between the lighter, heat-humidified chimney air and the outdoor atmosphere. Fill can be splash or film type.

Primary justification of these high first-cost products comes through reduction in auxiliary power requirements (elimination of fan energy), reduced property area, and elimination of recirculation and/or vapor plume interference. Materials used in chimney construction have been primarily steel-reinforced concrete; early timber structures had size limitations.

Mechanical-Draft Cooling Towers (Figure 11) shows five different designs for mechanical-draft (conventional) cooling towers. Fans may be on the inlet air side (forced-draft) or the exit air side (induced-draft). The type of fan selected, either centrifugal or axial, depends on external pressure needs, permissible sound levels, and energy usage requirements. Water is downflow; the air may be upflow (counterflow heat transfer) or horizontal flow (cross-flow heat transfer). Air entry may be through one, two, three, or all four sides of the tower. All four combinations (i.e., forced-draft counterflow, induced-draft counterflow, forced-draft cross-flow, and induced-draft cross-flow) have been produced in various sizes and configurations.

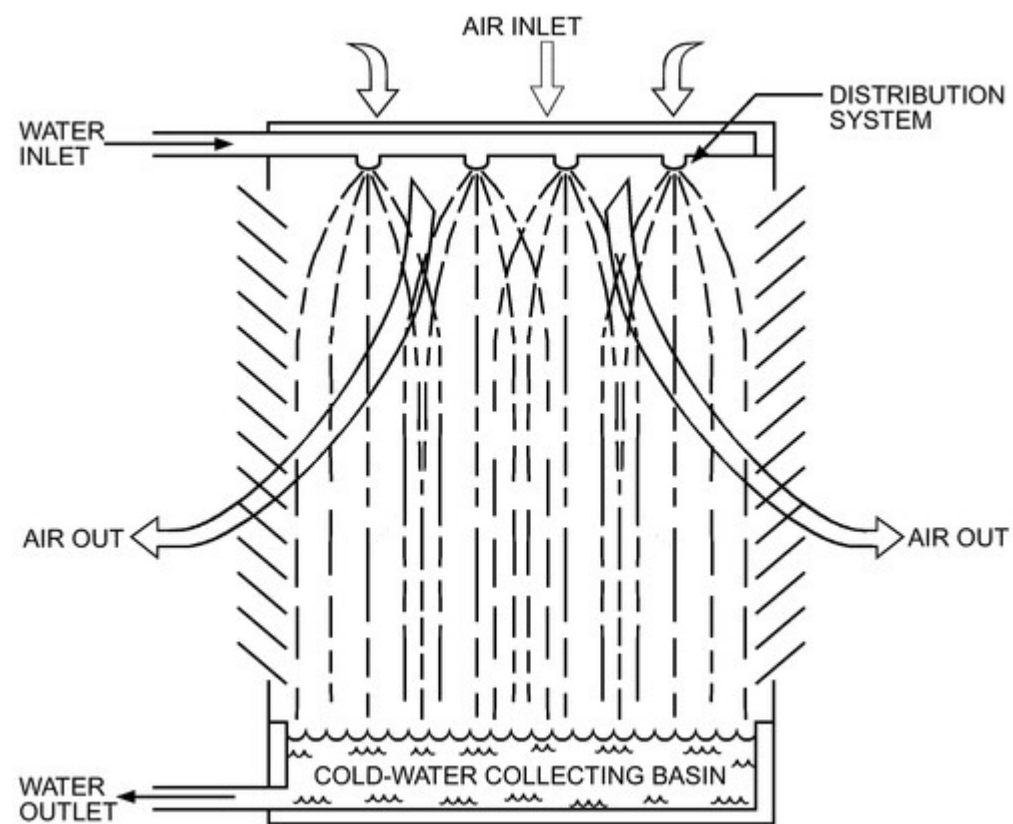


Figure 8. Vertical Spray Cooling Tower

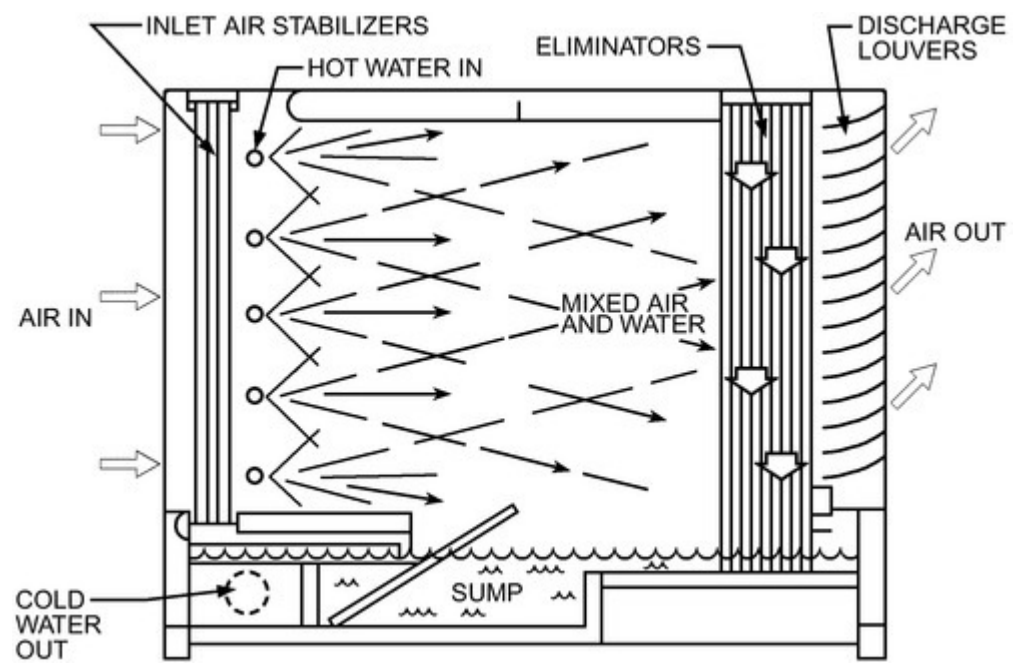


Figure 9. Horizontal Spray Cooling Tower

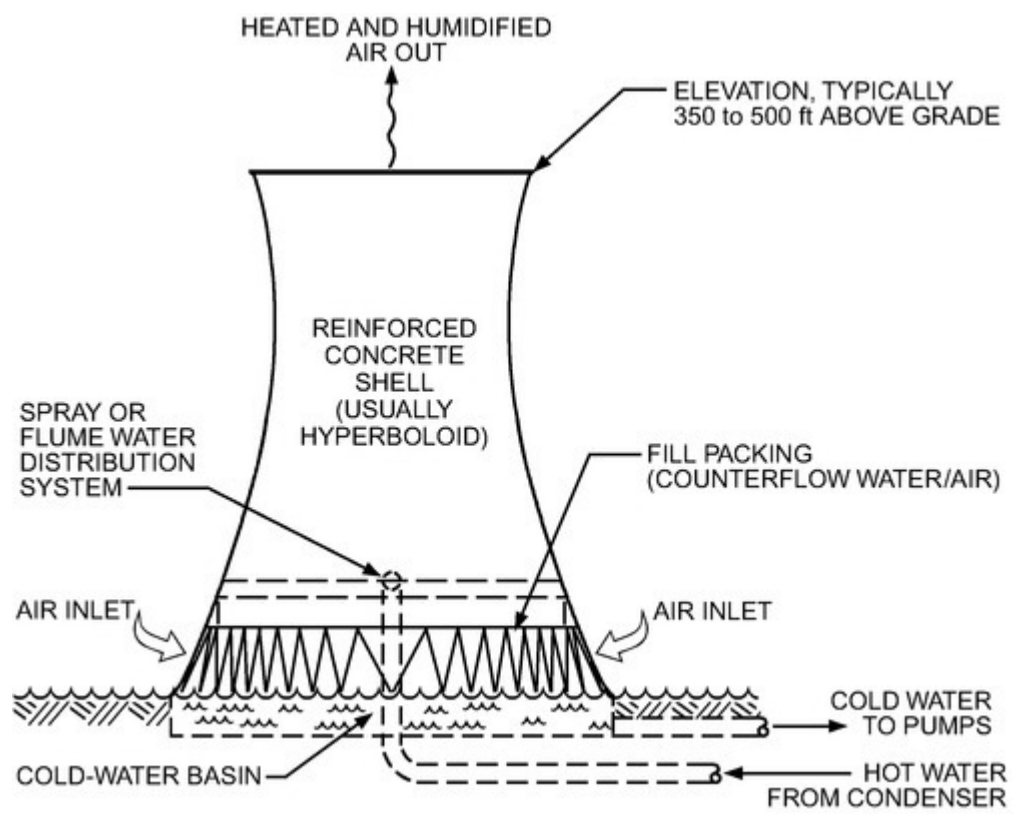


Figure 10. Hyperbolic Tower

Cooling towers are typically classified as either factory-assembled (Figure 12), where the entire cooling tower or a few large components are factory-assembled and shipped to the site for installation, or field-erected (Figure 13), where the tower is constructed completely on site.

Most factory-assembled cooling towers are of metal construction, usually galvanized steel. Other constructions include stainless steel and fiberglass-reinforced plastic (FRP) towers and components. Field-erected towers are predominantly framed of preservative-treated Douglas fir or redwood, with FRP used for special components and casing materials. Environmental concerns about cutting timber and wood preservatives leaching into cooling tower water have led to an increased number of cooling towers having FRP structural framing. Field-erected cooling towers may also be constructed of galvanized steel or stainless steel. Coated metals, primarily steel, are also used for complete towers or components. Concrete and ceramic materials are usually restricted to the largest towers (see the section on Materials of Construction).

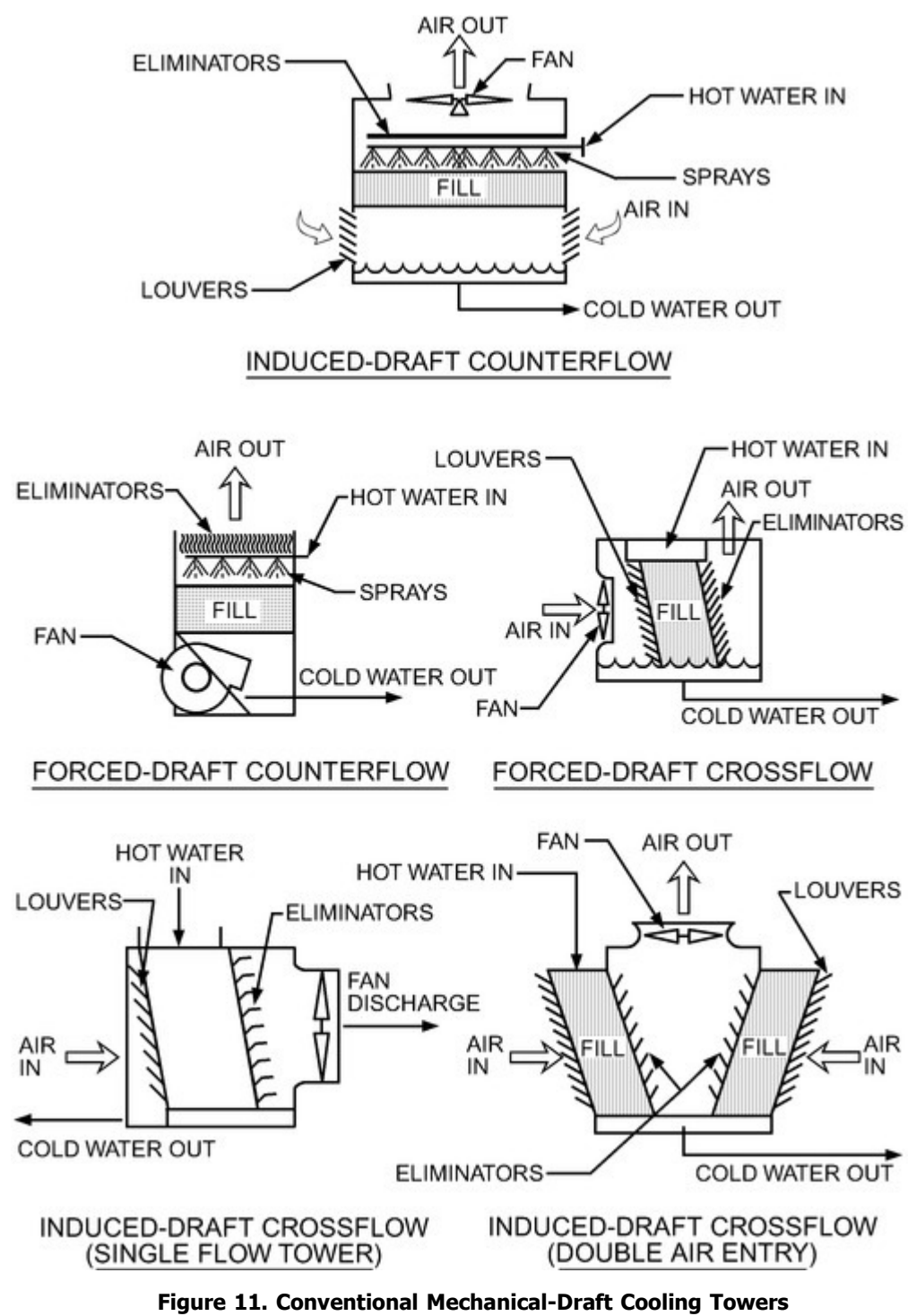


Figure 11. Conventional Mechanical-Draft Cooling Towers

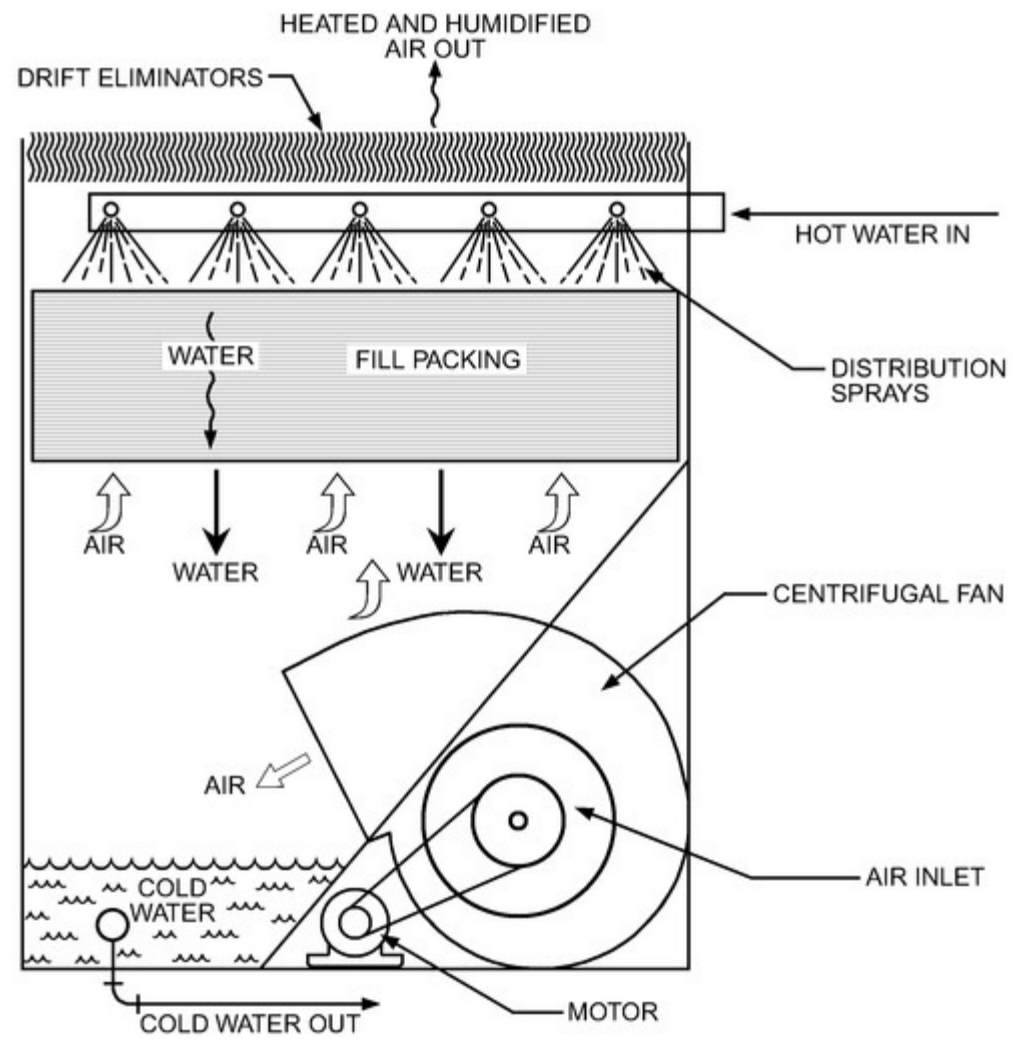


Figure 12. Factory-Assembled Counterflow Forced-Draft Cooling Tower

Special-purpose cooling towers containing a conventional mechanical-draft unit in combination with an air-cooled (finned-tube) heat exchanger are wet/dry cooling towers (Figure 14). They are used for either vapor plume reduction or water conservation. The hot, moist plumes discharged from cooling towers are especially dense in cooler weather. On some installations, limited abatement of these plumes is required to avoid restricted visibility on roadways, on bridges, and around buildings.

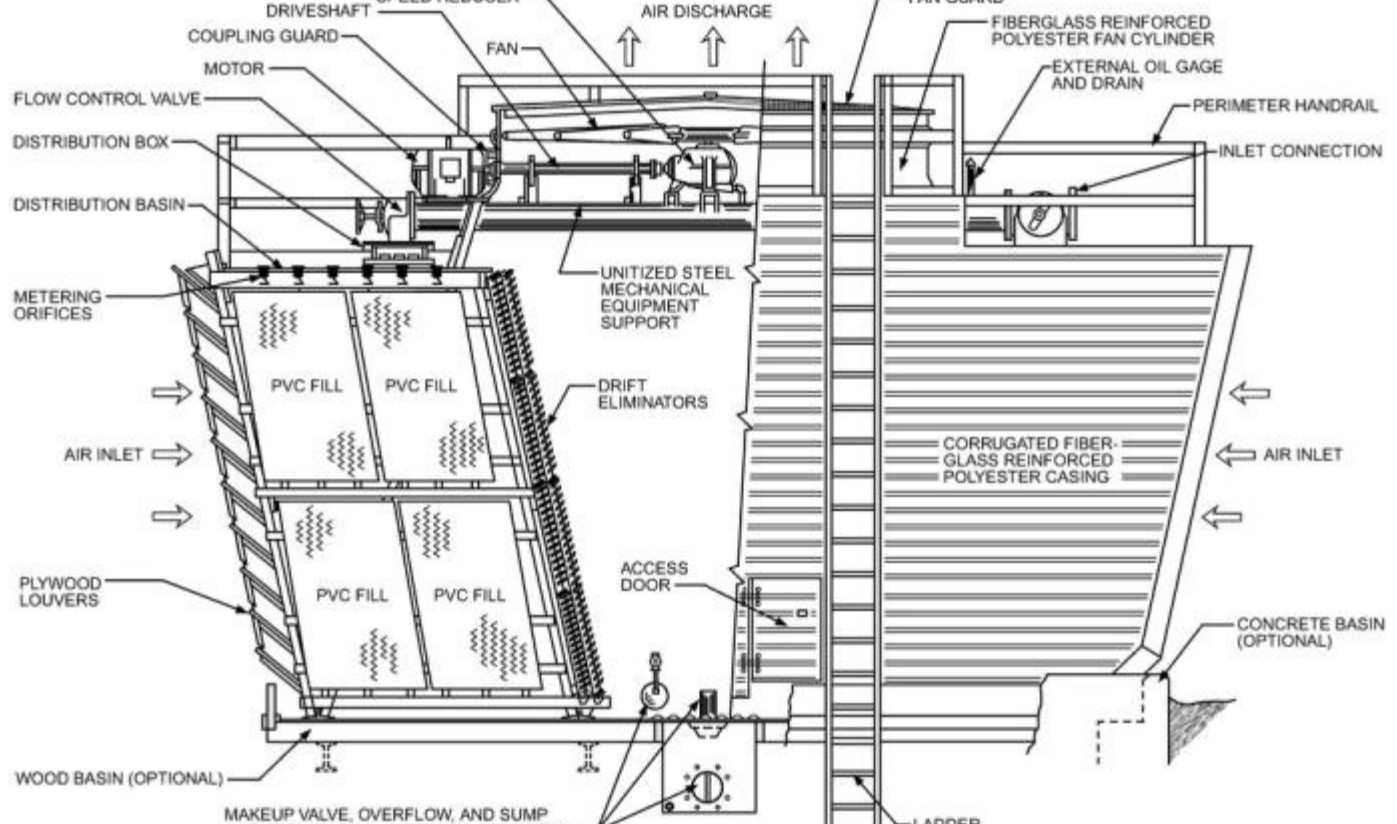


Figure 13. Field-Erected Cross-Flow Mechanical-Draft Cooling Tower

A vapor plume abatement cooling tower usually has a relatively small air-cooled component that tempers the leaving airstream to reduce the relative humidity and thereby minimize the fog-generating potential of the tower. Conversely, a water conservation cooling tower usually requires a large air-cooled component to significantly reduce water consumption and provide plume abatement. Some designs can handle heat loads entirely by the nonevaporative air-cooled heat exchanger portion during reduced ambient temperature conditions.

A variant of the wet/dry cooling tower is an evaporatively pre-cooled/air-cooled heat exchanger. It uses an adiabatic saturator (air pre-cooler/humidifier) to enhance summer performance of an air-cooled exchanger, thus conserving water compared to conventional cooling towers (annualized) (Figure 15). Evaporative fill sections usually operate only during specified summer periods, whereas full dry operation is expected below 50 to 70°F dry-bulb ambient conditions. Integral water pumps return the lower basin water to the upper distribution systems of the adiabatic saturators in a manner similar to closed-circuit fluid cooler and evaporative condenser products.

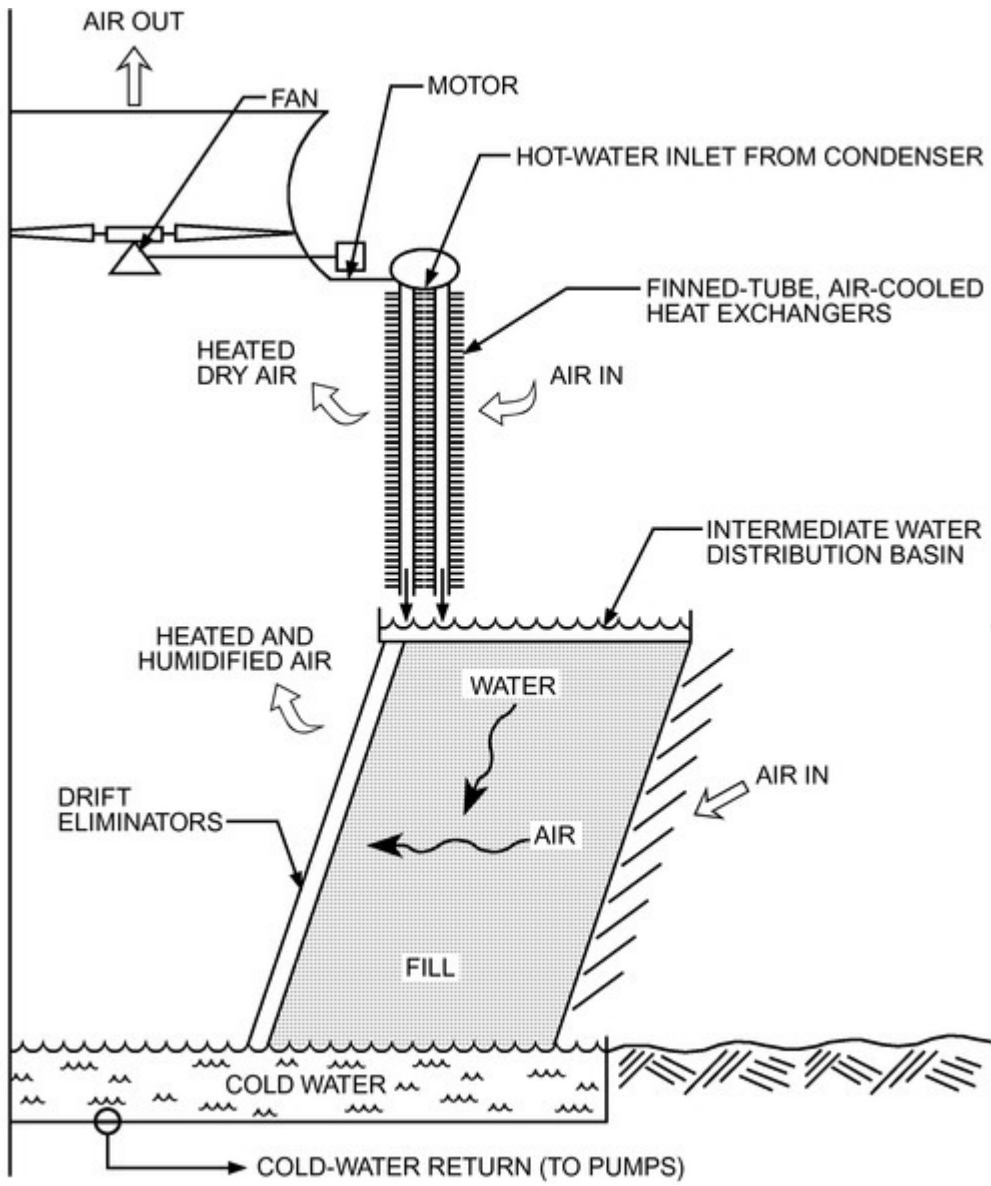


Figure 14. Combination Wet/Dry Cooling Tower

Other Methods of Direct Heat Rejection.

Ponds, Spray Ponds, Spray Module Ponds, and Channels. Heat dissipates from the surface of a body of water by evaporation, radiation, and convection. Captive lakes or ponds (artificial or natural) are sometimes used to dissipate heat by natural air currents and wind. This system is usually used in large plants where real estate is not limited.

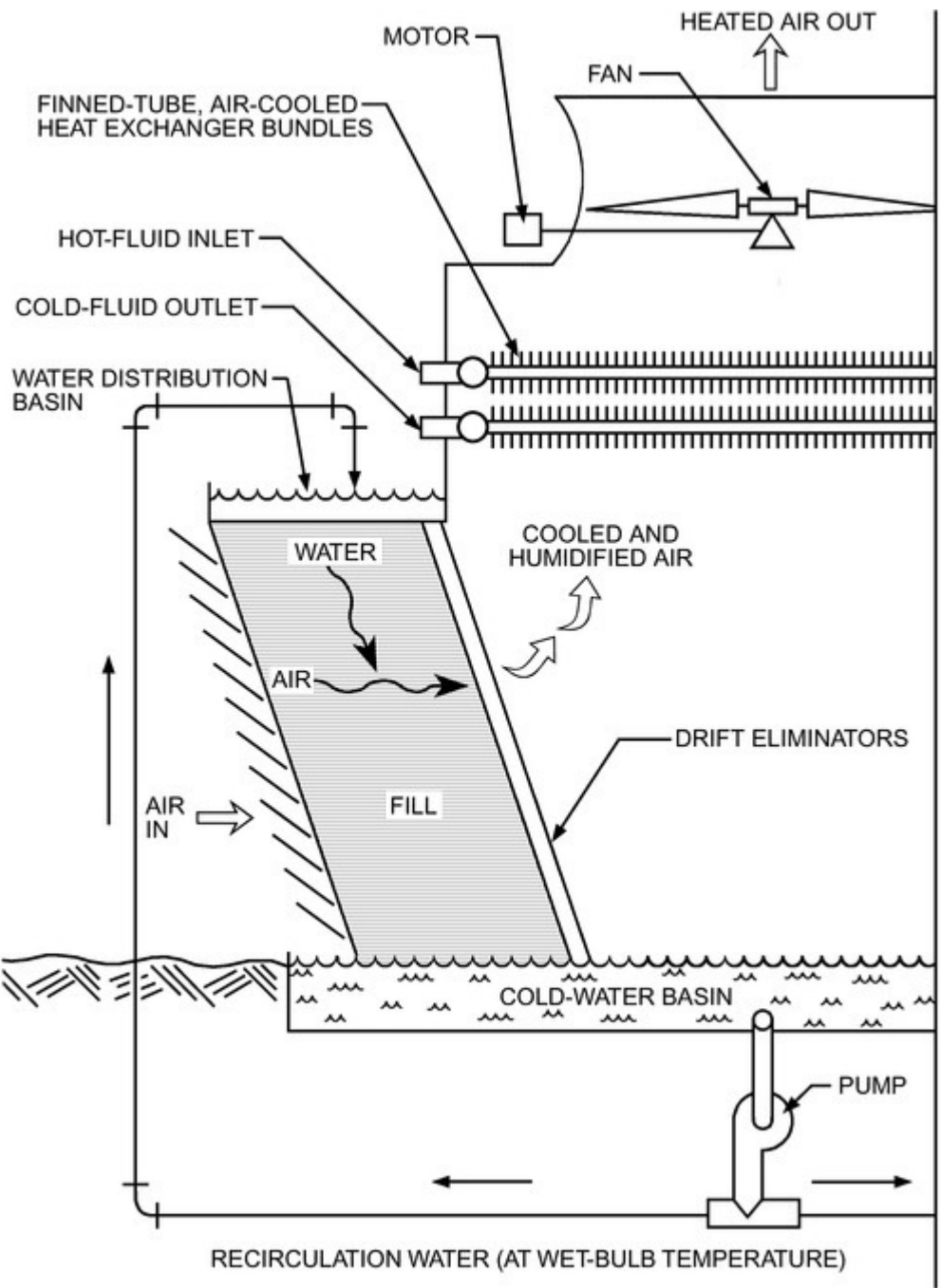


Figure 15. Adiabatically Saturated Air-Cooled Heat Exchanger

A pump-spray system above the pond surface improves heat transfer by spraying water in small droplets, thereby extending the water surface and bringing it into intimate contact with the air. Heat transfer is largely the result of evaporative cooling (see the section on Cooling Tower Theory). The system is a piping arrangement using branch arms and nozzles to spray circulated water into the air. The pond acts largely as a collecting basin. Temperature control, real estate demands, limited approach to the wet-bulb temperature, and winter operational difficulties have ruled out the spray pond in favor of more compact and more controllable mechanical- or natural-draft towers. Empirically derived relationships such as Equation (1) have been used to estimate cooling pond area. However, because of variations in wind velocity and solar radiation as well as the overall validity of the relationship itself, a substantial margin of safety should be added to the result.

$$w_p = \frac{A(95 + 0.425v)}{h_{fg}} [p_w - p_a] \tag{1}$$

where

- w_p = evaporation rate of water, lb/h
- A = area of pool surface, ft²
- v = air velocity over water surface, fpm
- h_{fg} = latent heat required to change water to vapor at temperature of surface water, Btu/lb
- p_w = saturation vapor pressure at dew-point temperature of ambient air, in. Hg
- p_a = saturation vapor pressure at temperature of surface water, in. Hg

Indirect-Contact Cooling Towers

Closed-Circuit Cooling Towers (Mechanical Draft). Both counterflow and cross-flow arrangements are used in forced- and induced-draft fan arrangements. The tubular heat exchangers are typically serpentine bundles, usually arranged for free gravity internal drainage. Pumps are integrated in the product to transport water from the lower collection basin to upper distribution basins or sprays. The internal coils (see Figure 5B) can be constructed from several materials, but galvanized steel, stainless steel, and copper predominate. Closed-circuit cooling towers, which are similar to evaporative condensers (see Chapter 39), are used extensively on water-source heat pump systems and screw compressor oil pump systems, and wherever the reduced maintenance and greater reliability of a closed-loop system are desired. Closed-circuit cooling towers also provide cooling for multiple heat loads on a centralized closed-loop system.

Indirect-contact cooling towers (see Figure 4) require a closed-circuit heat exchanger (usually tubular serpentine coil bundles) that is exposed to air/water cascades similar to the fill of a cooling tower. Some types include supplemental film or splash fill sections to augment the external heat exchange surface area. In Figure 6, air flows down over the coil, parallel to the recirculating water, and exits horizontally into the fan plenum. Recirculating water then flows over cooling tower fill, where it is further cooled by a second airstream before being reintroduced over the coil. Open- and closed-circuit cooling tower capacities are not directly comparable because of the intermediate step of heat transfer in the closed-circuit design. Closed-circuit cooling towers are more readily comparable to a combination of an open-circuit cooling tower and liquid-to-liquid heat exchanger, such as a plate-and-frame heat exchanger (see Figure 22).

Hybrid Cooling Towers

Hybrid cooling towers combine sensible, adiabatic, and evaporative cooling to reduce water and energy requirements compared to conventional cooling equipment.

Water savings are achieved through different operational combinations of these cooling types. When more adiabatic, direct evaporative, or indirect evaporative cooling is used, less energy is consumed at the expense of using more water. Conversely, when more direct sensible cooling is used, less water is consumed at the expense of using more energy. The following operational modes can be used singly or in combination.

Wet Mode (Figure 16). This mode uses only evaporative cooling during elevated temperature or load conditions. It optimizes fan energy and/or process fluid temperatures with increased water consumption from evaporation.

Dry/Wet Mode (Figure 17). The dry/wet mode simultaneously uses evaporative and sensible cooling when allowed by moderate temperature or load conditions. This mode meets load requirements while reducing water consumption from evaporation through increased fan energy consumption or modulating flow through the evaporative coil. It may also reduce plumes.

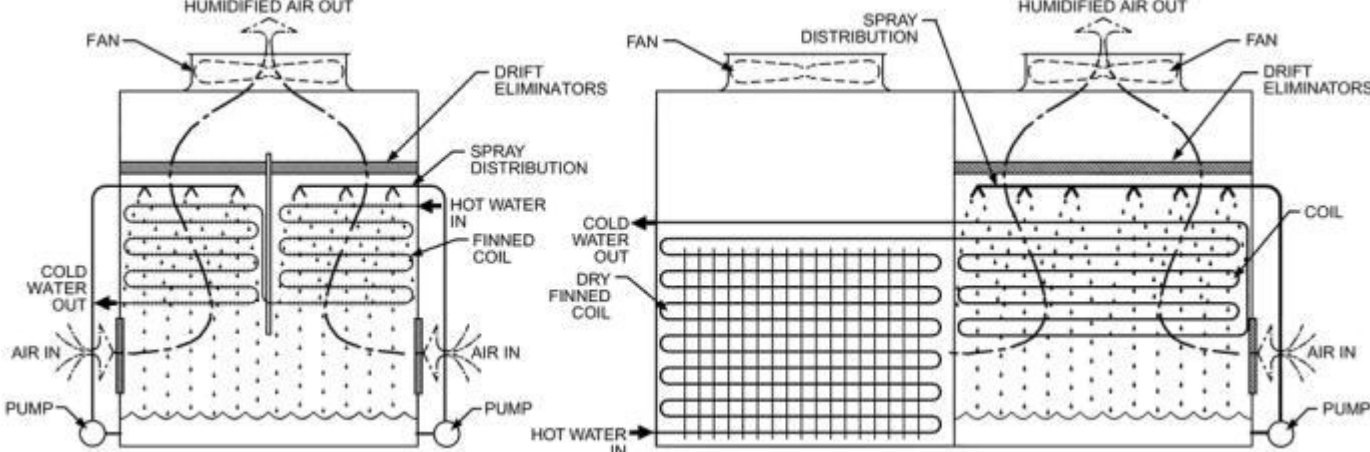


Figure 16. Hybrid Cooling Towers in Wet Operational Mode

Adiabatic Mode (Figure 18). This mode rejects heat through the dry coil, and the recirculating spray water merely serves to saturate and adiabatically precool incoming outdoor air. Adiabatic cooling of the incoming air results in lower air temperatures, which increases the rate of sensible heat transfer. Visible plume and water consumption are greatly reduced.

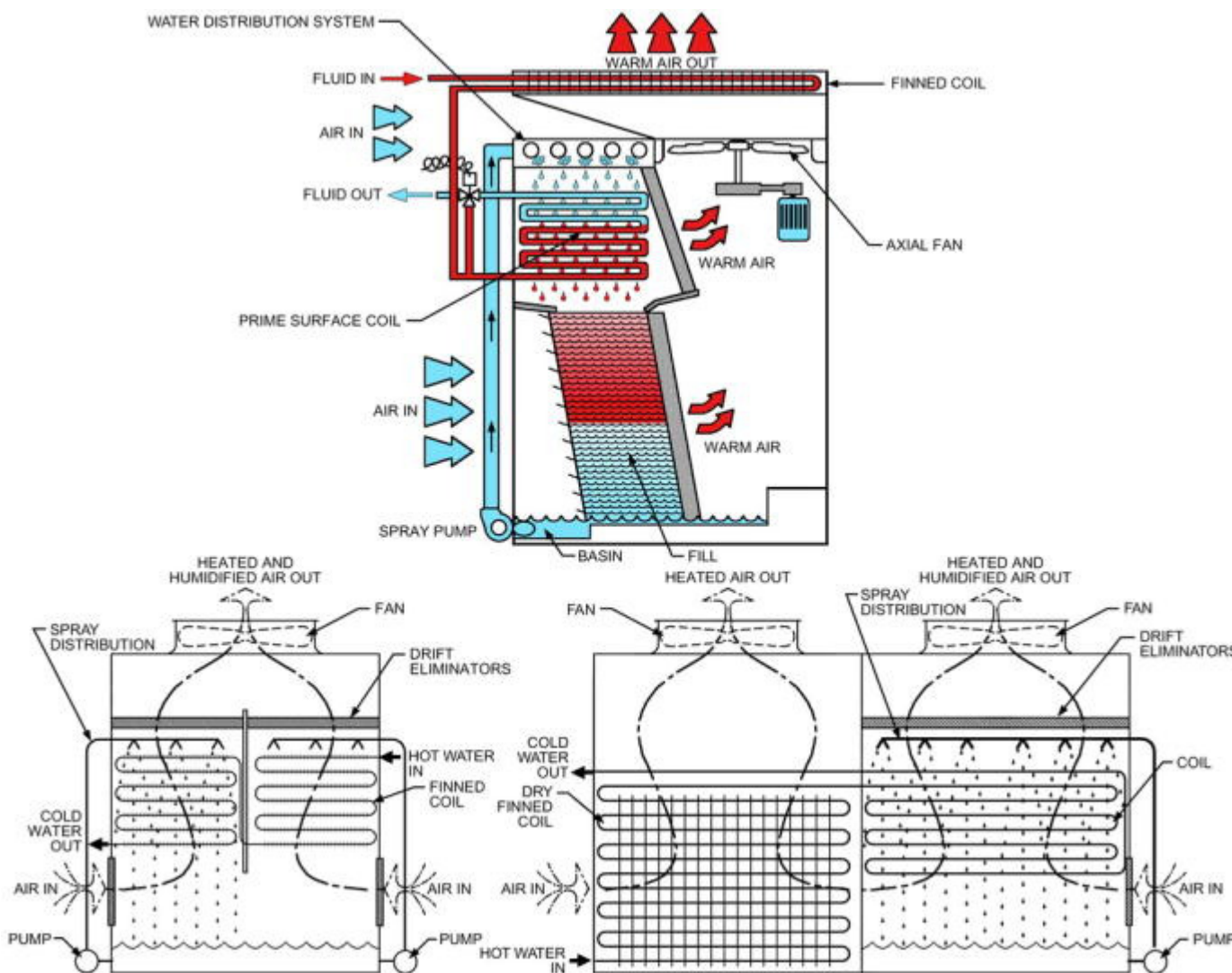


Figure 17. Hybrid Cooling Towers in Dry/Wet Operational Mode

Dry Mode (Figure 19). The dry mode uses sensible cooling when allowed by reduced load and/or ambient temperatures. This mode eliminates water consumption from evaporation while meeting load requirements through increased fan energy. Plume is avoided with this mode.

4. MATERIALS OF CONSTRUCTION

Materials for cooling tower construction are usually selected to meet the expected water quality and atmospheric conditions.

Wood. In the past, wood was used extensively for all static components except hardware, primarily on field-erected towers and occasionally on factory-assembled towers. Redwood and fir predominated, usually with postfabrication pressure treatment of waterborne preservative chemicals, typically chromated copper arsenate (CCA) or acid copper chromate (ACC). These microbiodical chemicals prevent the attack of wood-destructive organisms such as termites or fungi. Environmental restrictions on treatment chemicals, concerns about potential leaching of those chemicals into the environment, and variations in structural properties of individual wood members have reduced its popularity, and it has been largely replaced with fiber-reinforced plastics.

Metals. Steel with galvanized zinc is used for small and medium-sized installations. Hot-dip galvanizing after fabrication is used for larger weldments. Hot-dip galvanizing and cadmium and zinc plating are used for hardware. Brasses and bronzes are selected for special hardware, fittings, and tubing material. Stainless steels (principally 301L, 304, and 316) are often used for sheet metal, drive shafts, and hardware in exceptionally corrosive atmospheres or to extend unit life. Stainless steel cold-water basins are increasingly popular. Cast iron is a common choice for base castings, fan hubs, motor or gear reduction housings, and piping valve components. Metals coated with polyurethane and PVC are used selectively for special components. Two-part epoxy compounds and hybrid epoxy powder coatings are also used for key components or entire cooling towers.

Plastics. Fiberglass-reinforced plastic (FRP) materials are used for components such as structure, piping, fan cylinders, fan blades, casing, louvers, and structural connecting components. Polypropylene and acrylonitrile butadiene styrene (ABS) are specified for injection-molded components, such as fill bars and flow orifices. PVC is typically used as fill, eliminator, and lower materials. Reinforced plastic mortar is used in larger piping systems, coupled by neoprene O-ring-gasketed bell and spigot joints.

Graphite Composites. Graphite composite drive shafts are available for use on cooling tower installations. These shafts offer a strong, corrosion-resistant alternative to steel/stainless steel shafts and are often less expensive, more forgiving of misalignment, and transmit less vibration.

Concrete, Masonry, and Tile. Concrete is typically specified for cold-water basins of field-erected cooling towers and is used in piping, casing, and structural systems of the largest towers, primarily in the power and process industries. Special tiles and masonry are used when aesthetic considerations are important.

5. SELECTION CONSIDERATIONS

Selecting the proper water-cooling equipment for a specific application requires consideration of cooling duty, economics, required services, environmental conditions, maintenance requirements, and aesthetics. Many of these factors are interrelated, but they should be evaluated individually.

Because a wide variety of water-cooling equipment may meet the required cooling duty, factors such as height, length, width, volume of airflow, fan and pump energy consumption, materials of construction, water quality, and availability influence final equipment selection.

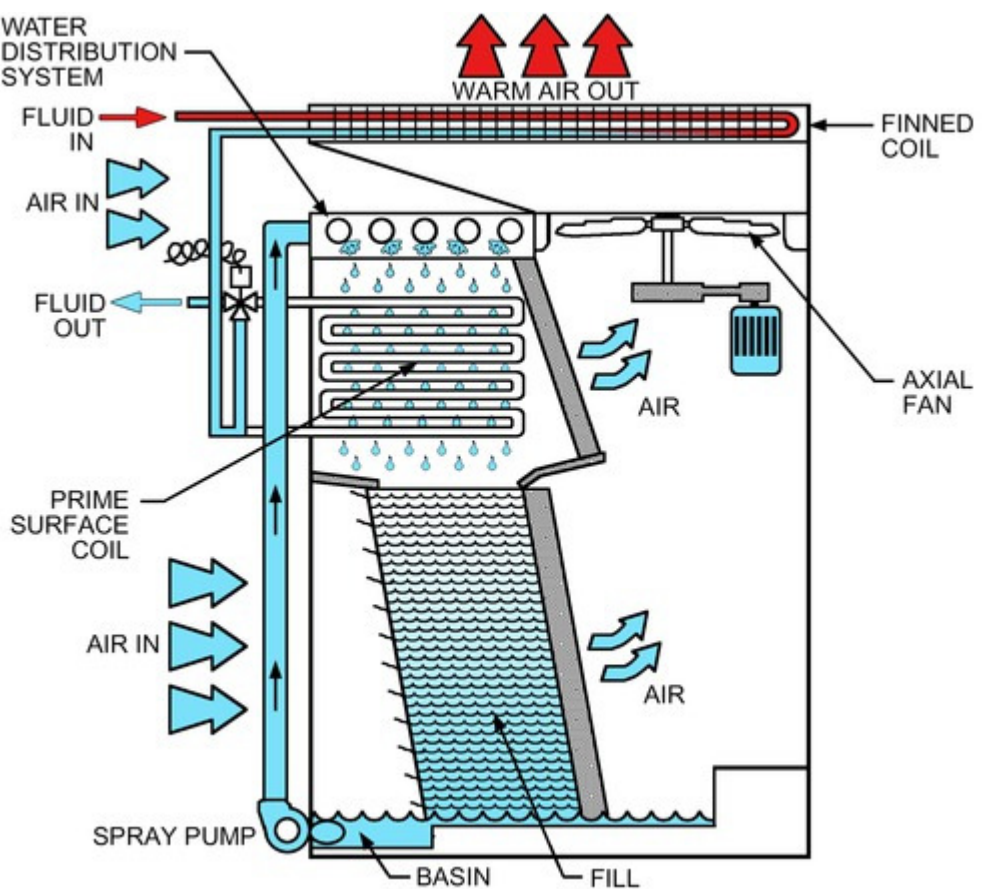


Figure 18. Hybrid Cooling Tower in Adiabatic Operational Mode

The optimum choice is generally made after an economic evaluation. Chapter 37 of the 2015 ASHRAE Handbook—HVAC Applications describes two common methods of economic evaluation: life-cycle costing and payback analysis. Each of these procedures compares equipment on the basis of total owning, operating, and maintenance costs.

Initial-cost comparisons consider the following factors:

- Erected cost of equipment
- Costs of interface with other subsystems, which include items such as
 - Basin grillage and value of the space occupied
 - Pumps and prime movers
 - Electrical wiring to pump and fan motors
 - Electrical controls and switchgear
 - Piping to and from the cooling tower (some designs require more inlet and discharge connections than others, thus affecting the cost of piping)

- Cooling tower basin, basin screens, overflow piping, and makeup lines, if not furnished by the manufacturer
- Shutoff and control valves, if not furnished by the manufacturer
- Walkways, ladders, etc., providing access to the tower, if not furnished by the manufacturer
- Fire protection sprinkler system

In evaluating owning and maintenance costs, consider the following major items:

- System energy costs (fans, pumps, etc.) on the basis of operating hours per year
- Energy demand charges
- Expected equipment life
- Maintenance and repair costs
- Money costs
- Life-cycle cost
- Water availability

Other factors are (1) safety features and safety codes; (2) conformity to building codes; (3) general design and rigidity of structures; (4) relative effects of corrosion, scale, or deterioration on service life; (5) availability of spare parts; (6) experience and reliability of manufacturers; (7) independent certification of thermal ratings; and (8) operating flexibility for economical operation at varying loads or during seasonal changes. In addition, equipment vibration, sound levels, acoustical attenuation, and compatibility with the architectural design are important. The following section details many of these more important considerations.

6. APPLICATION

This section describes some of the major design considerations, but the cooling tower manufacturer should be consulted for more detailed recommendations.

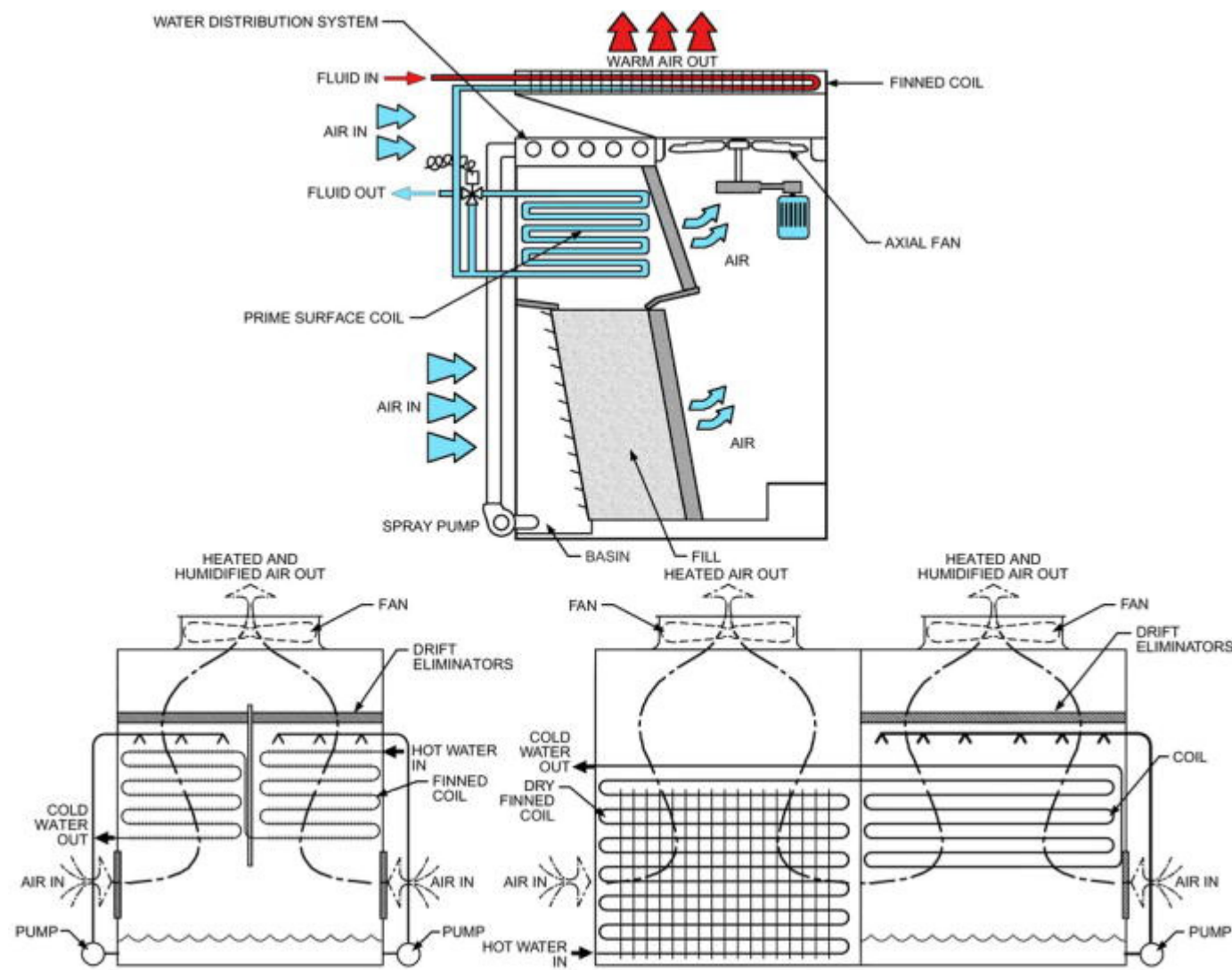


Figure 19. Hybrid Cooling Towers in Dry Operational Mode

Siting

When a cooling tower can be located in an open space with free air motion and unimpeded air supply, siting is normally not an obstacle to satisfactory installation. However, cooling towers are often situated indoors, against walls, or in enclosures. In such cases, the following factors must be considered:

- Sufficient free and unobstructed space should be provided around the unit to ensure an adequate air supply to the fans and to allow proper servicing.
- Cooling tower discharge air should not be deflected in any way that might promote recirculation [a portion of the warm, moist discharge air reentering the cooling tower ([Figure 20](#))]. Recirculation raises the entering wet-bulb temperature, causing increased hot water and cold water temperatures, and, during cold weather operation, can promote the icing of air intake areas. The possibility of air recirculation should be considered, particularly on multiple-tower installations.

Additionally, cooling towers should be located to prevent introducing the warm discharge air and any associated drift, which may contain chemical and/or biological contaminants, into the fresh air intake of the building that the tower is serving or into those of adjacent buildings.

Location of the cooling tower is usually determined by one or more of the following: (1) structural support requirements, (2) rigging limitations, (3) local codes and ordinances, (4) cost of bringing auxiliary services to the cooling tower, and (5) architectural compatibility. Sound, plume, and drift considerations are also best handled by proper site selection during the planning stage. For additional information on seismic and wind restraint, see [Chapter 55 of the 2015 ASHRAE Handbook—HVAC Applications](#).

Piping

Piping should be adequately sized according to standard commercial practice. All piping should be designed to allow expansion and contraction. If the cooling tower has more than one inlet connection, balancing valves should be installed to balance the flow to each cell properly. Positive shutoff valves should be used, if necessary, to isolate individual cells for servicing.

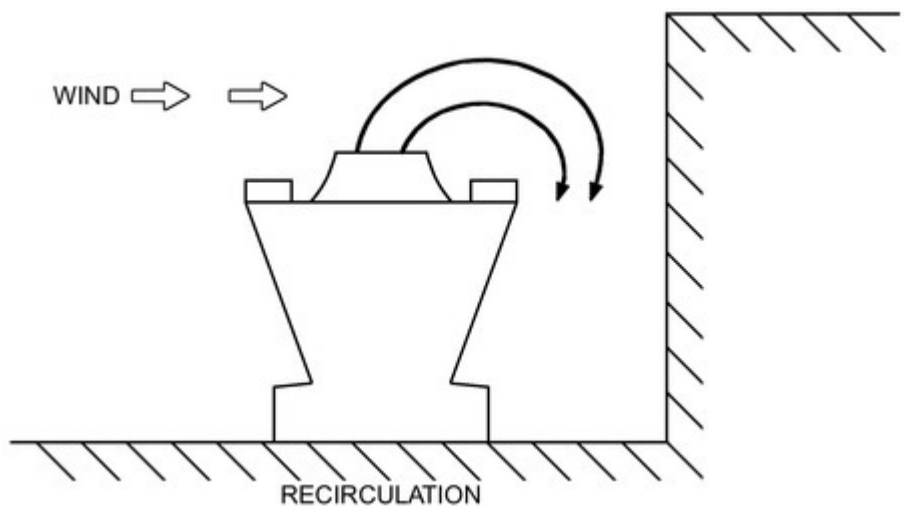


Figure 20. Discharge Air Reentering Cooling Tower

When two or more cooling towers operate in parallel, an equalizer line between the cooling tower basins handles imbalances in the piping to and from the units and changing flow rates that arise from obstructions such as clogged orifices and strainers. All heat exchangers, and as much tower piping as possible, should be installed below the operating water level in the cooling tower to prevent overflowing of the cooling tower at shutdown and to ensure satisfactory pump operation during start-up. Cooling tower basins must carry the proper amount of water during operation to prevent air entrainment into the water suction line. Basins should also have enough reserve volume between the operating and overflow levels to fill riser and water distribution lines on start-up and to fulfill the water-in-suspension requirement of the cooling tower. Unlike open cooling towers, closed-circuit cooling towers can be installed anywhere, even below the heat exchangers, as the fluid to be cooled is contained in a closed loop; the external spray water is self-contained within the closed-circuit cooling tower.

Capacity Control

Most cooling towers encounter substantial changes in ambient wet-bulb temperature and load during the normal operating season. Accordingly, some form of capacity control may be required to maintain prescribed system temperatures or process conditions.

Frequency-modulating controls for fan motor speed can provide virtually infinite capacity control and energy management. Previously, automatic, variable-pitch propeller fans were the only way to do this. However, these mechanically complex drive systems are more expensive and have higher sound levels, because they operate at full design speed only. They have been replaced by variable-frequency drives (VFDs) coupled with a standard fixed-pitch fan, thereby saving more fan energy and operating significantly more quietly than cycling fans, especially at less than full load.

Variable-frequency fan drives are economical and can save considerable energy as well as extend the life of the motor, fan, and drive (gearbox or V-belt) assembly compared to fan cycling or two-speed control. However, the following special considerations must be discussed with the cooling tower manufacturer and the supplier of the VFD:

- Care must be taken to avoid operating the fan system at a critical speed or a multiple thereof. **Critical speeds** are fan operating speeds identical to one of the natural frequencies of the fan assembly and/or supporting structure. At these speeds, fan resonance occurs, resulting in excessive vibration and possibly fan system failure, sometimes very quickly. Consult the tower manufacturer on what speeds (if any) must be avoided. Alternatively, the tower can be tested at start-up using an accelerometer to identify critical frequencies throughout the full speed range, though this is generally not necessary with pre-engineered, factory-assembled units. Critical frequencies, identified either by the manufacturer or through actual testing, must be locked out in the VFD skip frequency program.
- Some VFDs, particularly pulse-width modulating (PWM) drives, create overvoltages at the motor that can cause motor and bearing failures. The magnitude of these overvoltages increases significantly with the length of cable between the controller and the motor, so lead lengths should be kept as short as possible. Special motors, filters, or other corrective measures may be necessary to ensure dependable operation. Consult the cooling tower manufacturer and/or the VFD supplier. [Chapter 45](#) also has more information on variable-frequency drives.
- A VFD-compatible motor should be specified on all cooling towers with variable-frequency drive.
- Most VFDs can modulate down to 10% or less of full motor speed. However, a given cooling tower may have special limits below 25% speed. If operating below 25% speed, consult the cooling tower manufacturer on the possible limits of their equipment.

Fan cycling is another method of capacity control on cooling towers and has often been used on multiple-unit or multiple-cell installations. In nonfreezing climates, where close control of exit water temperature is not essential, fan cycling is an adequate and inexpensive method of capacity control. However, motor burnout from too-frequent cycling is a concern.

Two-speed fan motors or additional lower-power pony motors, in conjunction with fan cycling, can double the number of steps of capacity control compared to fan cycling alone. This is particularly useful on single-fan motor units, which would have only one step of capacity control by fan cycling. Two-speed fan motors provide the added advantage of reduced energy consumption at reduced load. Pony motors, which are typically sized for 1/3 of the power of the main motor, provide redundancy in case one motor fails in addition to energy savings.

It is more economical to operate all fans at the same speed than to operate one fan at full speed before starting the next. For example, two cells operating at half speed (12.5% of full-speed power) have similar cooling capacity as one cell operating at full speed and one cell with the fan off. However, two cells operating at half speed use one-fourth the power (12.5% + 12.5%) of the one cell operating at full speed (100%). [Figure 21](#) compares cooling tower fan power versus speed for single-, two-, and variable-speed fan motors.

Modulating dampers in the discharge of centrifugal blower fans are also used for cooling tower capacity control, as well as for energy management. In some cases, modulating dampers may be used with two-speed motors. Note that modulating dampers have been replaced by variable-frequency drives for these purposes.

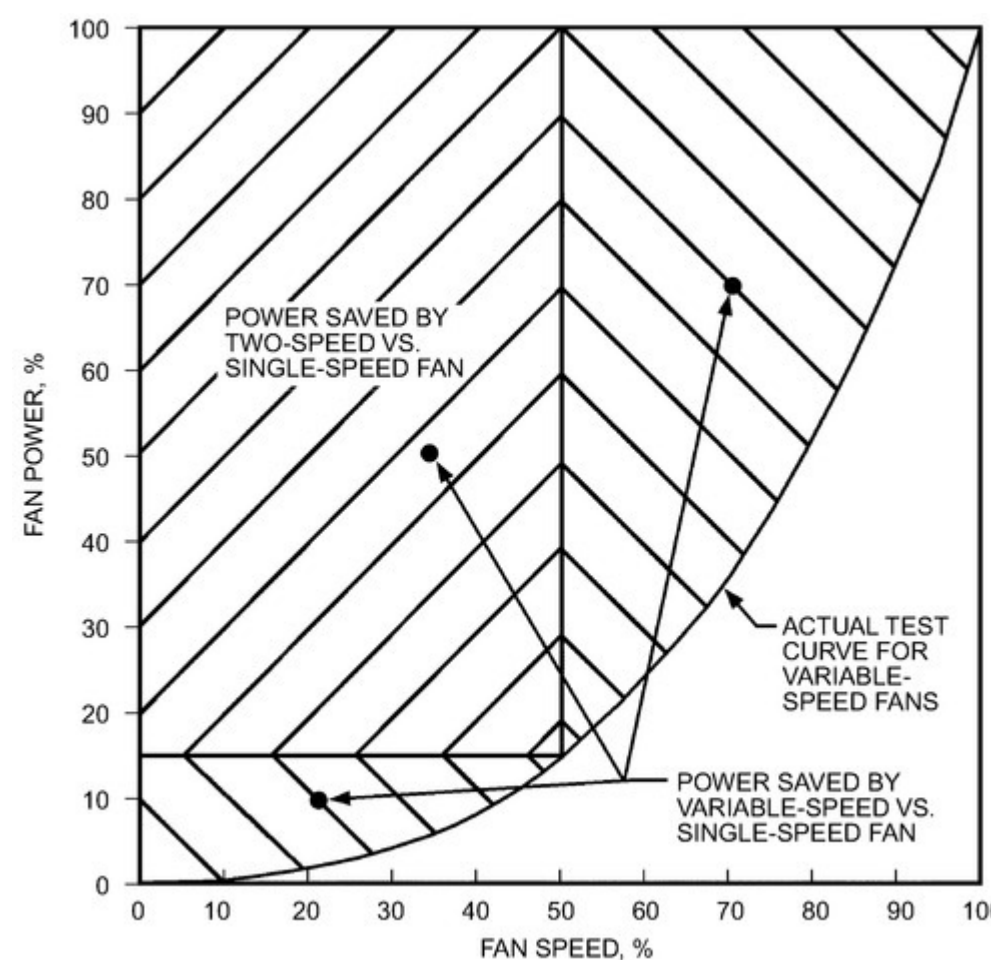


Figure 21. Cooling Tower Fan Power Versus Speed (White 1994)

Cooling towers that inject water to induce airflow through the cooling tower have various pumping arrangements for capacity control. Multiple pumps in series or two-speed pumping provide capacity control and also reduce energy consumption.

Modulating water bypasses for capacity control should be used only after consultation with the cooling tower manufacturer. This is particularly important at low ambient conditions in which the reduced water flow can promote freezing within the cooling tower.

Energy can be saved in multicell tower installations by operating multiple cells together at part-load conditions instead of turning individual cells off.

To take advantage of the energy savings of operating two cells at half speed instead of one at full speed, it is important to control all fans together and maintain water flow over all cells. For cooling towers with two-speed motors, all cells should be brought up to the lower speed first (usually half speed) before switching any cells to full speed. For VFD operation, all cells should be started and ramped up and down together. Operating the fans in this way maximizes tower energy savings. In some cases, this can cut the annual cooling tower energy usage by half or more.

In addition to fan motor control, flow control can also offer substantial savings. Process, simplicity, and/or cost of piping drives many installations to pipe one tower cell or pairs of cells for each process instead of connecting all processes together with a common manifold. An example of this is one chiller per cooling tower cell for installations with multiple chillers. The thought is that when one chiller is turned off, the operator can also turn off the associated cooling tower and pump. Although this can save energy, more energy can be saved by keeping the cooling tower cell on and spreading the condenser return water from the remaining chillers over all tower cells. For the previous two-cell example, the operation consists of two cooling towers on, one chiller on, one pump on. In essence, each cooling tower cell operates at half of design flow. Half flow equals half heat load per cell, which in turn equals half fan speed and 1/8 the power draw per cell, or 1/4 (1/8 + 1/8) the full-speed power of one cell. Combining this with fan motor control yields the most efficient method of tower capacity control. To use this flow control strategy, the following must be considered:

- Consult the cooling tower manufacturer on reduced-flow operation. Not all cooling towers in all situations can operate at 50% flow or less. The cooling tower manufacturer can best clarify the limits of their product and how best to operate.
- Consult the manufacturer if operating at reduced flow in freezing environments. Manufacturers may require special options or control recommendations for this type of operation. For more information, see the section on Winter Operation.
- Operating the cooling tower at some reduced flows may create dry spots in film fill heat transfer media. Under the right conditions and water quality, this can cause scale build-up, which reduces the tower's effective capacity. Consult the manufacturer on the product's capabilities and any special requirements or options.

Water-Side Economizer (Free Cooling)

With an appropriately equipped and piped system, using the cooling tower for free cooling during reduced load and/or reduced ambient conditions can significantly reduce system energy consumption. Because the cooling tower's cold-water temperature drops as the load and ambient temperature drop, the water temperature will eventually be low enough to serve the load directly, allowing the energy-intensive chiller to be shut off. [Figures 22 to 24](#) outline three methods of free cooling but do not show all of the piping, valving, and controls that may be necessary for the functioning of a specific system. Compared to air-side economizers, water-side economizers can significantly reduce the risk of both particulate and gaseous contamination as well as humidity issues by reducing the amount of outdoor air required beyond that needed for ventilation. Additionally, using a closed-circuit cooling tower or an open cooling tower with a liquid-to-liquid heat exchanger and the associated piping and controls is often less expensive than the addition of large outdoor air flowovers and dampers and the associated control system required with air-side economizer systems for larger facilities, especially data centers. Additionally, the water-side economizer system may offer the benefit of improved reliability.

Maximum use of free cooling occurs when a drop in the ambient temperature reduces the need for dehumidification. Therefore, higher temperatures in the chilled-water circuit can normally be tolerated during the free-cooling season and are beneficial to the system's heating/cooling balance. In many cases, typical 45°F chilled-water temperatures are allowed to rise to 55°F or higher in free cooling. This maximizes cooling tower usage and minimizes system energy consumption. Some applications require a constant chilled-water supply temperature, which can reduce the hours of free cooling operation, depending on ambient temperatures.

If the spray water temperature is allowed to fall too low, freezing may be a concern. Close control of spray water temperature per the manufacturer's recommendations minimizes unit icing and helps ensure trouble-free operation. Refer to the guidelines from the manufacturer and to the section on Winter Operation in this chapter.

Indirect Free Cooling. This type of cooling separates the condenser-water and chilled-water circuits and may be accomplished in the following ways:

- A separate heat exchanger in the system (usually plate-and-frame) allows heat to transfer from the chilled-water circuit to the condenser-water circuit by total bypass of the chiller system ([Figure 22](#)).
- An indirect-contact, closed-circuit evaporative cooling tower ([Figures 5, 6, and 2](#)) also allows indirect free cooling and eliminates the need for an additional heat exchanger. Its use is covered in the following section on Direct Free Cooling.
- In vapor migration system ([Figure 23](#)), bypasses between the evaporator and condenser allow migratory flow of refrigerant vapor to the condenser; they also allow gravity flow of liquid refrigerant back to the evaporator without compressor operation. Not all chiller systems are adaptable to this arrangement, and those that are may offer limited load capability under this mode. In some cases, auxiliary pumps enhance refrigerant flow and, therefore, load capability.

Direct Free Cooling. This type of cooling involves interconnecting the condenser-water and chilled-water circuits so the cooling tower water serves the load directly ([Figure 24](#)). In this case, the chilled-water pump is normally bypassed so design water flow can be maintained to the cooling tower. The primary disadvantage of the direct free-cooling system is that it allows the relatively dirty condenser water to contaminate the clean chilled-water system. Although filtration systems (either side-stream or full-flow) minimize this contamination, many specifiers consider it to be an overriding concern. Using a closed-circuit (indirect-contact) cooling tower eliminates this contamination. During summer, water from the cooling tower is circulated in a closed loop through the condenser. During winter, water from the cooling tower is circulated in a closed loop directly through the chilled-water circuit.

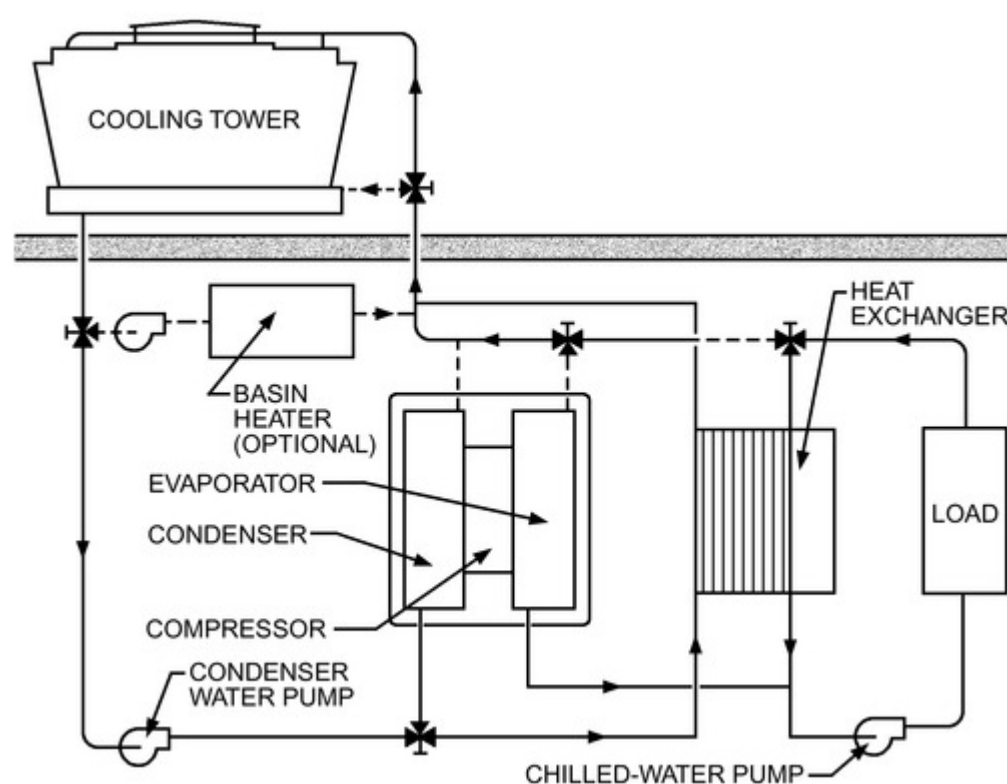


Figure 22. Free Cooling by Auxiliary Heat Exchanger

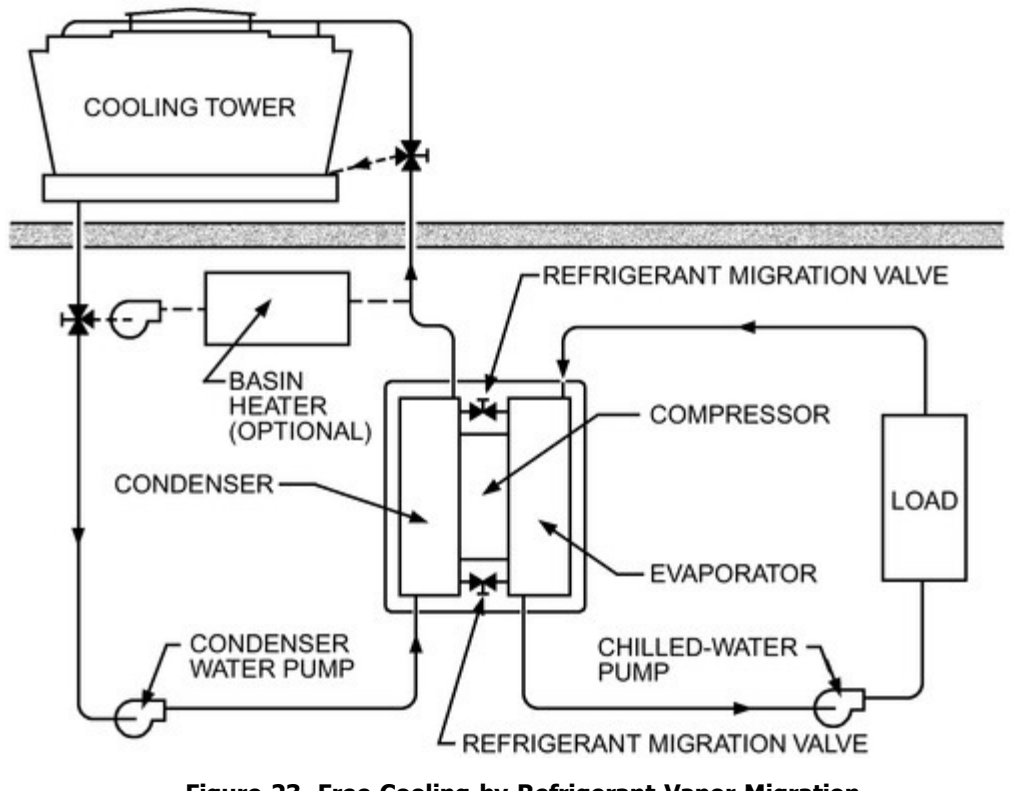


Figure 23. Free Cooling by Refrigerant Migration

Winter Operation

When a cooling tower is to be used in freezing climates, the following design and operating considerations are necessary.

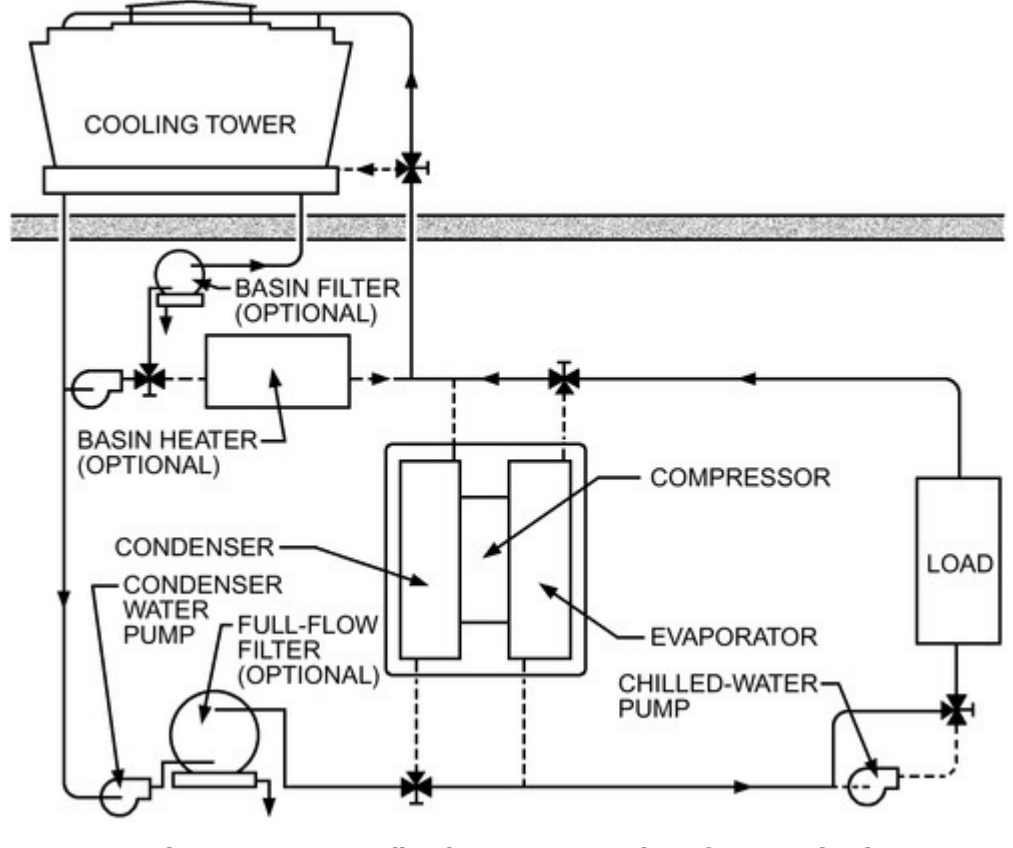


Figure 24. Free Cooling by Interconnection of Water Circuits

Open Circulating Water. Direct-contact cooling towers can be winterized by a suitable method of capacity control that maintains the temperature of water leaving the cooling tower well above freezing. In addition, during cold weather, regular visual inspections of the cooling tower should be made to ensure all controls are operating properly. On induced-draft axial fan cooling towers, fans may be periodically operated in reverse, usually at low speed, to deice the air intake areas. Using fan cycling or (preferably) variable-frequency drives minimizes the possibility of icing by matching cooling tower capability with the load. Some icing can be expected at the cold air/water interface. Good operating practice includes frequent inspections of the cooling tower, especially during extremely cold weather. Recirculation of moist discharge air on forced-draft equipment can cause ice formation on inlet air screens and fans. Installing vibration cutout switches can minimize the risk of damage from ice formation on rotating equipment.

Closed Circulating Water. Precautions beyond those mentioned for open circulating water must be taken to protect the fluid inside the heat exchanger of a closed-circuit fluid cooling tower. When system design allows, the best protection is to use an antifreeze solution. When this is not possible, supplemental heat must be provided to the heat exchanger, and the manufacturer should be consulted about the amount of heat input required. Positive-closure damper hoods are also available from many manufacturers to reduce heat loss from the coil section and thus reduce the amount of heat input required.

All exposed piping to and from the closed-circuit cooling tower should be insulated and heat traced. In case of a power failure during freezing weather and where water is used in the system, the heat exchanger should include an emergency draining system.

Basin Water. Freeze protection for basin water in an idle cooling tower or closed-circuit cooling tower can be obtained by various means. A good method is to use an auxiliary sump tank located in a heated space. When a remote sump is impractical, auxiliary heat must be supplied to the cooling tower basin to prevent freezing. Common sources are electric immersion heaters and steam and hot-water coils. Towers that do not operate in the winter should be cleaned and drained. Consult the cooling tower manufacturer for the exact heat requirements to prevent freezing at design winter temperatures. Using dry cooling or closed-circuit cooling towers during winter operation eliminates the potential for ice built-up on air inlet louvers and may allow the basin water to be drained.

All exposed water lines susceptible to freezing should be protected by electric heat tape or cable and insulation. This precaution applies to all lines or portions of lines that have water in them when the cooling tower is shut down.

Sound

Sound has become an important consideration in the selection and siting of outdoor equipment such as cooling towers and other evaporative cooling devices. Many communities have enacted legislation that limits allowable sound levels of outdoor equipment. Even if legislation does not exist, people who live and work near a cooling tower installation may object if the sound intrudes on their environment. Because the cost of correcting a sound problem may exceed the original cost of the cooling tower, sound should be considered in the early stages of system design.

To determine the acceptability of cooling tower sound levels in a given environment, the first step is to establish a noise criterion for the area of concern. This may be an existing or pending code or an estimate of sound levels that will be acceptable to those living or working in the area. The second step is to estimate the sound levels generated by the tower at the critical area, taking into account the effects of the cooling tower installation geometry and the distance from the tower to the critical area. Often, the cooling tower manufacturer can supply sound rating data on a specific unit that serve as the basis for this estimate. Lastly, the noise criterion is compared to the estimated tower sound levels to determine the acceptability of the installation.

In cases where the installation may present a sound problem, several potential solutions are available. It is good practice to situate the cooling tower as far as possible from any sound-sensitive areas. Many cooling towers are available with optional low-sound fans using wider-chord blades selected at lower tip speeds. Variable-frequency drives offer the additional advantage of reducing or eliminating the sound level fluctuations that occur with cycling of single- or two-speed motors; fluctuations are usually considered more objectionable than a constant or a slowly varying sound level. VFDs can also be programmed to run at lower speeds during light-load periods, such as at night, if these correspond to critical sound-sensitive periods.

In critical situations, effective solutions may include barrier walls between the cooling tower and the sound-sensitive area, acoustical treatment of the cooling tower, or using low-sound fans. Attenuators specifically designed for the tower are available from most manufacturers. It may also be practical to install a cooling tower larger than would normally be required and lower the sound levels by operating the unit at reduced fan speed. This also has the advantage of saving energy because of the smaller fan motor(s), which can quickly pay for the added investment in the larger cooling tower. For additional information on sound control, see [Chapter 48 of the 2015 ASHRAE Handbook—HVAC Applications](#).

Drift

Water droplets become entrained in the airstream as it passes through the cooling tower. Although eliminators strip most of this water from the discharge airstream, some discharges from the tower as drift. The rate of drift loss from a cooling tower is a function of cooling tower configuration, eliminator design, airflow rate through the tower, and water loading. Generally, an efficient eliminator design reduces maximum drift loss to between 0.001 and 0.005% of the water circulation rate. Because drift contains the minerals of the makeup water (which may be concentrated three to five times) and often contains water treatment chemicals, cooling towers should not be placed near parking areas, large windowed areas, or architectural surfaces sensitive to staining or scale deposits.

Fogging (Cooling Tower Plume)

Warm air discharged from a cooling tower is essentially saturated. Under certain operating conditions, the ambient air surrounding the tower cannot absorb all of the moisture in the tower discharge airstream, and the excess condenses as fog. Fogging may be predicted by projecting a straight line on a psychrometric chart from the cooling tower entering air conditions to a point representing the discharge conditions ([Figure 25](#)). A line crossing the saturation curve indicates fog generation; the greater the area of intersection to the left of the saturation curve, the more intense the plume. Fog persistence depends on its original intensity and on the degree of mechanical and convective mixing with ambient air that dissipates the fog.

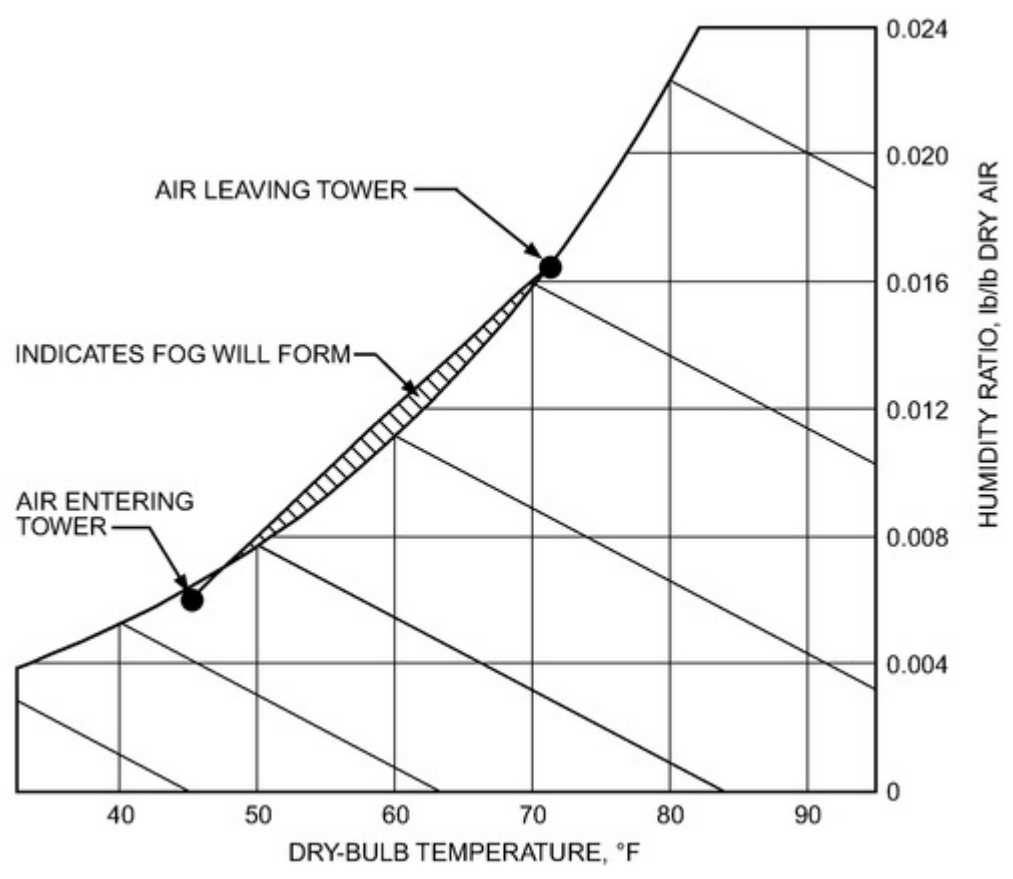


Figure 25. Fog Prediction Using Psychrometric Chart

Methods of reducing or preventing fogging have taken many forms, including heating the cooling tower exhaust with natural gas burners or hot-water or steam coils, installing precipitators, and spraying chemicals at the tower exhaust. However, such solutions are generally costly to operate and are not always effective. The simplest solution is to allow the leaving water temperature to drop below design, which helps reduce the temperature difference between the water and the ambient air.

On larger, field-erected installations, combination wet/dry cooling towers, which combine the normal evaporative portion of a tower with a finned-tube dry surface heat exchanger section (in series or in parallel), afford a more practical means of plume control. In such units, the saturated discharge air leaving the evaporative section is mixed within the cooling tower with the warm, relatively dry air off the finned-coil section to produce a subsaturated air mixture leaving the cooling tower. In some closed-circuit hybrid cooling tower designs, the dry and wet heat exchange sections combine to abate plume. This is accomplished by (1) reducing the amount of water evaporated by the wet coil by handling some of the heat load sensibly with the dry heat exchanger, and (2) simultaneously heating the discharge air with the incoming process fluid in the dry heat exchanger. In colder weather, these units can operate completely dry, eliminating plume altogether.

Often, however, the most practical solution to tower fogging is to locate the cooling tower where visible plumes, should they form, will not be objectionable. Accordingly, when selecting cooling tower sites, the potential for fogging and its effect on tower surroundings, such as large windowed areas or traffic arteries, should be considered.

Maintenance

Usually, the cooling tower manufacturer furnishes operating and maintenance manuals that include recommendations for procedures and intervals as well as parts lists for the specific unit. These recommendations should be followed when formulating the maintenance program for the cooling tower. Efficient operation and thermal performance of a cooling tower depend not only on mechanical maintenance, but also on cleanliness. Accordingly, cooling tower owners should incorporate the following as a basic part of their maintenance program.

- Periodic inspection of mechanical equipment, fill, and both hot- and cold-water basins to ensure that they are maintained in a good state of repair.
- Periodic draining and cleaning of wetted surfaces and areas of alternate wetting and drying to prevent accumulation of dirt, scale, or biological organisms, such as algae and slime, in which bacteria may develop.
- Proper treatment of circulating water for biological control and corrosion, in accordance with accepted industry practice.
- Systematic documentation of operating and maintenance functions. This is extremely important because without it, no policing can be done to determine whether an individual has actually adhered to a maintenance policy.

Inspections

The following should be checked daily (no less than weekly) in an informal walk-through inspection. Areas requiring attention have been loosely grouped for clarity, although category distinctions are often hazy because the areas are interdependent.

Performance. Optimum performance and safety depend on the operation of each individual component at its designed capability. A single blocked strainer, for instance, can adversely affect the capacity and efficiency of the entire system. Operators should always be alert to any degradation in performance, as this usually is the first sign of a problem and is invaluable in pinpointing minor problems before they become major. Consult the equipment manufacturers to obtain specific information on each piece of equipment (for both maintenance and technical characteristics), and keep manuals handy for quick reference.

Check and record all water and refrigerant temperatures, pump pressures, outdoor conditions, and pressure drops (differential pressure) across condensers, heat exchangers and filtration devices. This record helps operators become familiar with the equipment as it operates under various load conditions and provides a permanent record that can be used to calculate flow rates, assess equipment efficiency, expedite diagnostic procedures, and adjust maintenance and water treatment regimens to obtain maximum performance from the system.

For those units with water-side economizers using plate heat exchangers, check temperature and pressure differentials daily for evidence of clogging or fouling.

Major Mechanical Components. During cooling tower inspections, be alert for any unusual noise or vibration from pumps, motors, fans, and other mechanical equipment. This is often the first sign of mechanical trouble. Operators thoroughly familiar with their equipment generally have little trouble recognizing unusual conditions. Also listen for cavitation noises from pumps, which can indicate blocked strainers.

Check the cooling tower fan and drive system assembly for loose mounting hardware, condition of fasteners, grease and oil leaks, and noticeable vibration or wobble when the fan is running. Excessive vibration can rapidly deteriorate the tower.

Observe at least one fan start and stop each week. If a fan has a serious problem, lock it out of operation and call for expert assistance. To be safe, do not take chances by running defective fans.

Fan and drive systems should be professionally checked for dynamic balance, alignment, proper fan pitch (if adjustable), and vibration whenever major repair work is performed on the fan or if unusual noises or vibrations are present. It is good practice to have these items checked at least once every third year on all but the smallest cooling towers. Any vibration switches should be checked for proper operation at least annually.

Verify calibration of the fan thermostat periodically to prevent excessive cycling and to ensure that the most economical temperature to the chiller is maintained.

Cooling Tower Structure. Check the tower structure and casing for water and air leaks as well as deterioration. Inspect louvers, fill, and drift eliminators for clogging, excessive scale, or algal growth. Clean as necessary, using high-pressure water and taking care not to damage fragile fill and eliminator components.

Watch for excessive drift (water carryover), and take corrective action as required. Drift is the primary means of *Legionella* transmission by cooling towers and evaporative condensers (see *ASHRAE Standard 188 and Guideline 12* for recommendations on control of *Legionella*). Deteriorated drift eliminators should be replaced. Many older cooling towers have drift eliminators that contain asbestos. In the United States, deteriorated asbestos-type eliminators should as a rule be designated friable material and be handled and disposed of in a manner approved by the Environment Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA).

Check the cooling tower basin, structural members and supports, fasteners, safety rails, and ladders for corrosion or other deterioration and repair as necessary. Replace deteriorated cooling tower components as required.

Water Distribution and Quality. Check the hot-water distribution system frequently, and clear clogged nozzles as required. Water distribution should be evenly balanced when the system is at rated flow and should be rechecked periodically. Cooling towers with open distribution pans benefit from covers, which retard algal growth. Pressurized water distribution systems "shaded" by eliminators also slow growth of algae.

The basin water level should be within the manufacturer's range for normal operating level, and high enough to allow most solids to settle out, thereby improving water quality to the equipment served by the cooling tower.

Cooling tower water should be clear, and the surface should not have an oily film, excessive foaming, or scum. Oil inhibits heat transfer in cooling towers, condensers, and other heat exchangers and should not be present in cooling tower water. Foam and scum can indicate excess organic material that can provide nutrients to bacteria (Rosa 1992). If such conditions are encountered, contact the water treatment specialist, who will take steps to correct the problem.

Check the cold-water basin in several places for corrosion, accumulated deposits, and excessive algae, because sediments and corrosion may not be uniformly distributed. Corrosion and microbiological activity often occur under sediments. Cooling tower outlet strainers should be in place and free of clogging.

Do not neglect the strainers in the system. In-line strainers may be the single most neglected component in the average installation. They should be inspected and, if necessary, cleaned each time the cooling tower is cleaned. Pay particular attention to the small, fine strainers used on auxiliary equipment such as computer cooling units and blowdown lines.

Blow down chilled-water risers frequently, particularly on systems using direct free cooling. Exercise all valves in the system periodically by opening and closing them fully.

For systems with water-side economizers, maintaining good water quality is paramount to prevent fouling of the heat exchanger or chilled-water system, depending on the type of economizer used.

Check, operate, and enable winterization systems well before freezing temperatures are expected, to allow time to obtain parts and make repairs as necessary. Ensure that sediments do not build up around immersion heater elements, because this will cause rapid failure of the elements.

Maintain sand filters in good order, and inspect the media bed for channeling at least quarterly. If channeling is found, either replace or clean the media as soon as possible. Do not forget to carefully clean the underdrain assembly while the media is removed. If replacing the media, use only that which is specified for cooling towers. Do not use swimming pool filter sand in filters designed for cooling towers and evaporative condensers.

Centrifugal separators rarely require service, although they must not be allowed to overflow with contaminants. Verify proper flow rate, pressure drop, and purge operation.

Check bag and cartridge filters as necessary. Clean the cooling tower if it is dirty.

Cleanliness. Cooling towers are excellent air washers, and the water quality in a given location quickly reflects that of the ambient air (Hensley 1985). A typical 200-ton cooling tower operating 1000 hours may assimilate more than 600 lb of particulate matter from airborne dust and the makeup water supply (Broadbent et al. 1992). Proximity to highways and construction sites, air pollution, and operating hours are all factors in cooling tower soil loading.

Design improvements in cooling towers that increase thermal performance also increase air scrubbing capability (Hensley 1985). Recommendations by manufacturers regarding cleaning schedules are, therefore, to be recognized as merely guidelines. The actual frequency of cleanings should be determined at each location by careful observation and system history. Sand filters, bag filters, centrifugal separators, water treatment programs, etc., may not be sufficient to take the place of a physical cleaning. They are designed to improve water quality and the effectiveness of water treatment, as well as help maintain optimal heat transfer surfaces. Recent advancements in cleaning technologies include basin sweeping systems that in many cases can replace physical cleanings. Basin sweeping systems that can be connected to mechanical filtration devices such as separators and sand filters are readily available and offer an excellent means of continuously cleaning cooling tower basins. Depending on basin depth, a flow rate of 1.0 gpm/ft² is typically used for sizing basin sweeping systems. Note that regular cleaning of a cooling tower should not be expected to replace water treatment.

Cooling tower should not be allowed to become obviously fouled, but should be cleaned often enough that visible sedimentation and biological activity (algae and slime) are easily controlled by water treatment between cleanings. The tower is the only component in the condenser loop that can be viewed easily without system shutdown, so it should be considered an indicator of total system condition and cleanliness.

Water treatment should not be expected to protect surfaces it cannot reach, such as the metal or wood components under accumulated sediments. Biocides are not likely to be effective unless used in conjunction with a regular cleaning program. Poorly maintained systems create a greater demand on the biocide because organic sediments neutralize the biocide and tend to shield bacterial cells from the chemical, thus requiring higher and more frequent doses to keep microbial populations under control (Broadbent et al. 1992; McCann 1988). High concentrations of an oxidizing biocide can contribute to corrosion. Keeping the cooling tower clean reduces the breeding grounds and nutrients available to the microbial organisms (ASHRAE 1989; Broadbent 1989; Metz 1986, 1988).

Proper cleaning procedures address the entire cooling tower, including not only the cold-water basin but also the distribution system, strainers, eliminators, casing, fan and fan cylinders, and louvers. The water treatment specialist should be advised and consulted prior to and following the cleaning.

It is recommended that personnel involved wear high-efficiency particulate air (HEPA) type respirators, gloves, goggles, and other body coverings approved by the appropriate agency, such as the U.S. Department of Labor Occupational Health & Safety Administration (OSHA) or National Institute for Occupational Safety and Health (NIOSH) in the United States. This is especially true if the cleaning procedures involve the use of high-pressure water, air, and steam (ASHRAE 1989) or wet/dry vacuum equipment. If any chemicals are used, they must be handled according to their material safety data sheets (MSDS), available from the chemical supplier.

Operation in Freezing Weather. During operation in freezing weather, the cooling tower should be inspected more frequently, preferably daily, for ice formation on fill, louvers, fans, etc. This is especially true when the system is being operated outside the cooling tower design parameters, such as when the main system is shut down and only supplementary units (e.g., computer cooling equipment) are operating. Ice on fan and drive systems are dangerous and can destroy the fan. Moderate icing on fill and louvers is generally not dangerous but can cause damage if allowed to build up.

In some cases, closed-circuit cooling towers meet load requirements in dry operating mode, thus eliminating the need to spray water over the coils. This allows the basin to be drained. A remote sump or a high dry operation switch point is recommended to be able to better handle unseasonably warm days during winter months. This minimizes the need for system operators to refill the cold-water basin on warmer days and then drain the basin when colder weather returns. Finned coils can also be used to the design dry operation switch point. Note that the unit fan operates at full speed, drawing 100% of the motor power at the design dry switch point, significantly increasing the fan operating energy (minus the spray pump energy, which is off in this mode). However, when operating in wet mode with spray water over the coils, fan energy is only a small fraction of that required with dry operation.

Follow the manufacturer's specific recommendations both for operation in freezing temperatures and for decing methods such as low-speed reversal of fan direction for short periods of time. Monitor the operation of winterization equipment, such as immersion heaters and heat-tracing tape on makeup lines, to ensure that they are working properly. Check for conditions that could render the freeze protection inoperable, such as tripped breakers, closed valves, and erroneous temperature settings.

Help from Manufacturers. Equipment manufacturers will provide assistance and technical publications on the efficient operation of their equipment; some even provide training. Also, manufacturers can often provide names of reputable local service companies that are experienced with their equipment. Most of these services are free or of nominal cost.

Water Treatment

The quality of water circulating through an evaporative cooling system significantly affects the overall system efficiency, degree of maintenance required, and useful life of system components. Because the water is cooled primarily by evaporation of a portion of the circulating water, the concentration of dissolved solids and other impurities in the water can increase rapidly. Also, appreciable quantities of airborne impurities, such as dust and gases, may enter during operation. Depending on the nature of the impurities, they can cause scaling, corrosion, and/or silt deposits.

Simple blowdown (discharge of a small portion of recirculating water to a drain) may be adequate to control scale and corrosion on sites with good-quality makeup water, but it will not control biological contaminants, including *Legionella pneumophila*. All cooling tower systems should be treated to restrict biological growth, and many benefit from treatment to control scale and corrosion. For a complete and detailed description of water treatment, see [Chapter 49 of the 2015 ASHRAE Handbook—HVAC Applications](#). ASHRAE *Standard 188* and *Guideline 12* should also be consulted for recommendations regarding control of *Legionella*. Specific recommendations on water treatment, including control of biological contaminants, can be obtained from any qualified water treatment supplier.

White Rust

A common material of construction for factory assembled cooling towers is galvanized steel. Galvanizing is a process by which steel substrate is protected by a zinc coating for corrosion protection. The zinc coating is applied in a process that alloys the protective coating directly with the steel substrate, providing a mechanical barrier to the environment as well as electrochemical resistance to corrosion. If the zinc coating is breached, the zinc becomes a sacrificial anode providing cathodic corrosion protection of the steel.

Protective zinc surfaces must be treated to form a protective surface layer that reduces chemical activity (passivation) to maintain corrosion protection. Specific water conditions must be met to develop and maintain a passive zinc surface, including pH control, preventing mechanical abrasion by solids, corrosion inhibitors, moderate hardness, and moderate alkalinity. Additional information is available from manufacturers or position papers from organizations such as the Cooling Technology Institute (CTI) and Association of Water Technologies (AWT).

7. PERFORMANCE CURVES

The combination of flow rate and heat load dictates the range a cooling tower must accommodate. The entering air wet-bulb temperature and required system temperature level combine with cooling tower size to balance the heat rejected at a specified approach. The performance curves in this section are typical and may vary from project to project. Computerized selection and rating programs are also available from many manufacturers to generate performance ratings and curves for their equipment.

Cooling towers can accommodate a wide diversity of temperature levels, ranging as high as 150 to 160°F hot-water temperature in the hydrocarbon processing industry. In the air-conditioning and refrigeration industry, cooling towers are generally used in the range of 90 to 115°F hot water temperature. A typical standard design condition for such cooling towers is 95°F hot water to 85°F cold water, and 78°F wet-bulb temperature. A means of evaluating the typical performance of a cooling tower system is shown in [Figures 26 to 29](#). The example tower was selected for the air flow rate of 3 gpm per nominal ton when cooling water from 95 to 85°F at 78°F entering wet-bulb temperature ([Figure 26](#)).

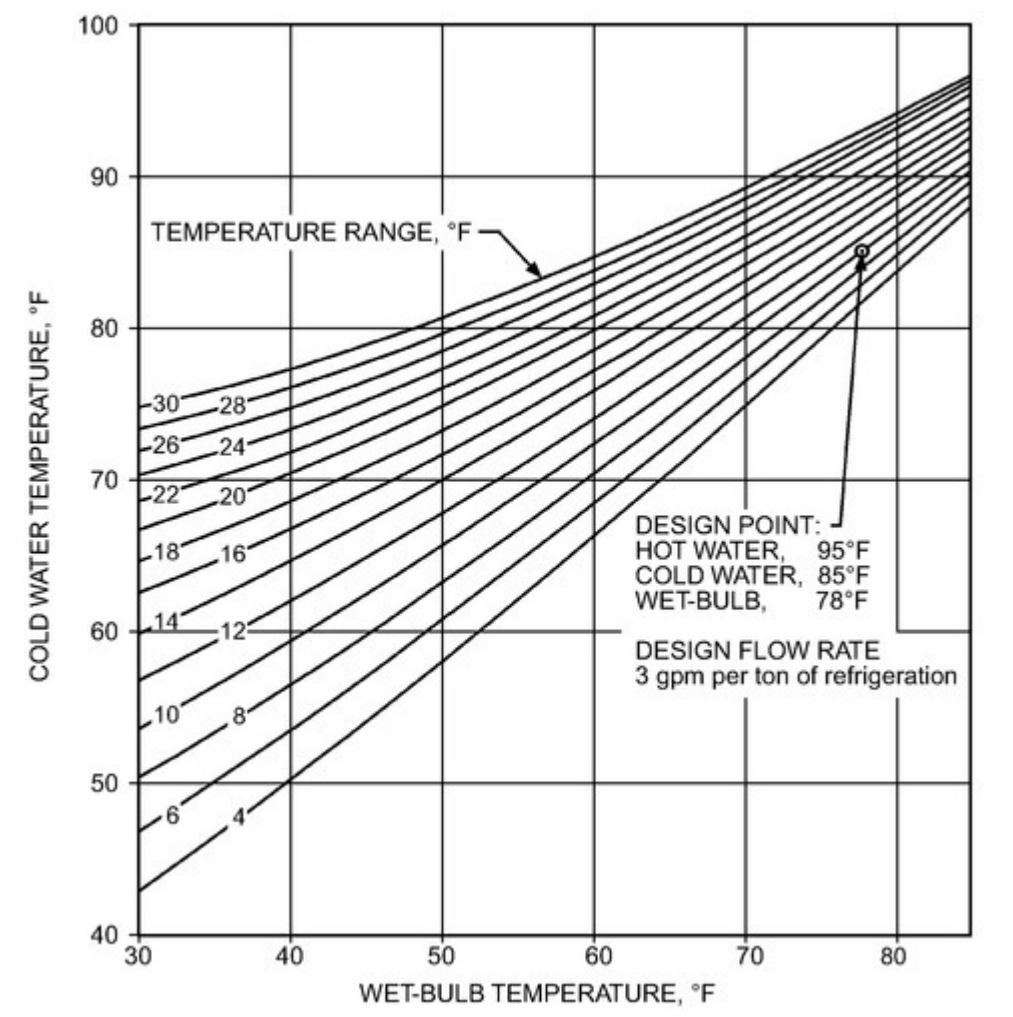


Figure 26. Cooling Tower Performance—100% Design Flow

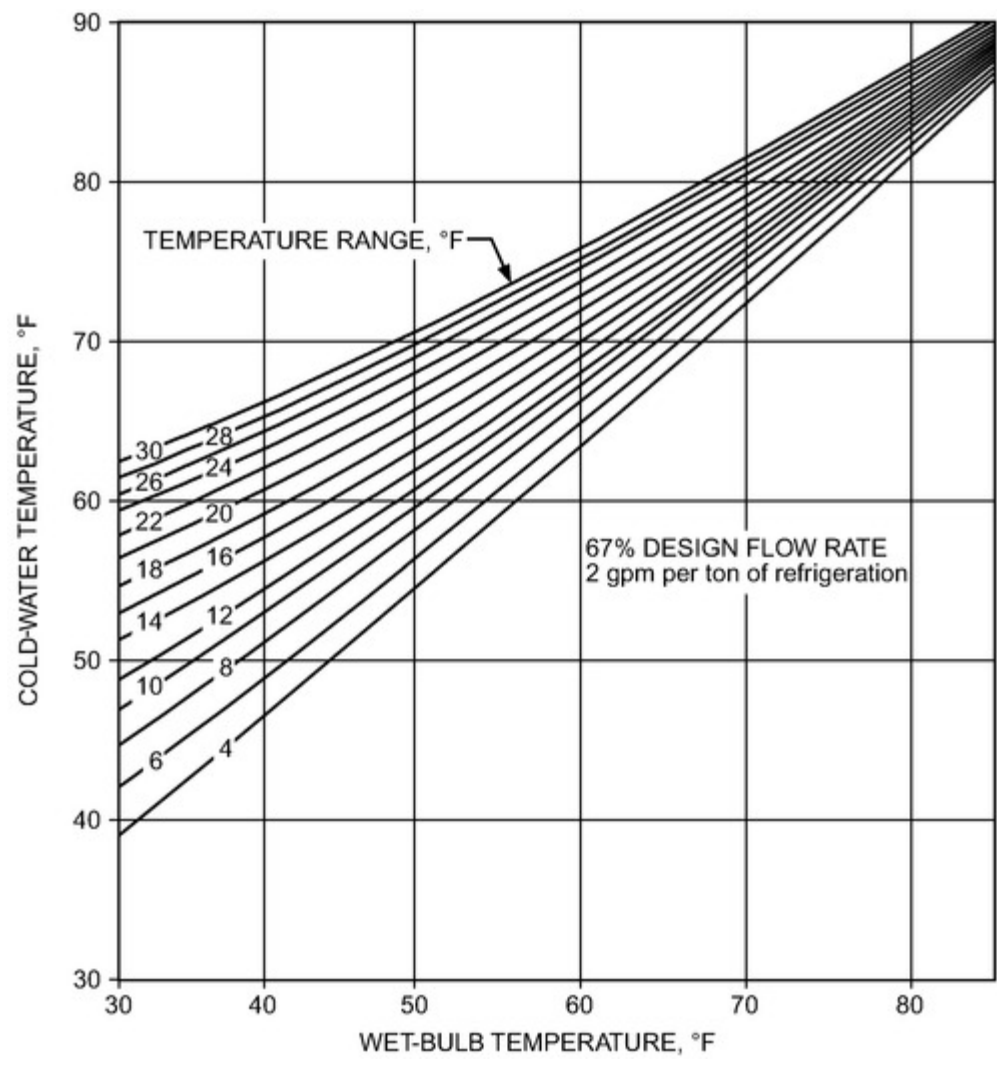


Figure 27. Cooling Tower Performance—67% Design Flow

When operating at other wet bulbs or ranges, the curves may be interpolated to find the resulting temperature level (hot and cold water) of the system. When operating at other flow rates (2, 4, and 5 gpm per nominal ton), this same cooling tower performs at the levels described by the titles of [Figures 27 to 29](#), respectively. Intermediate flow rates may be interpolated between charts to find resulting operating temperature levels.

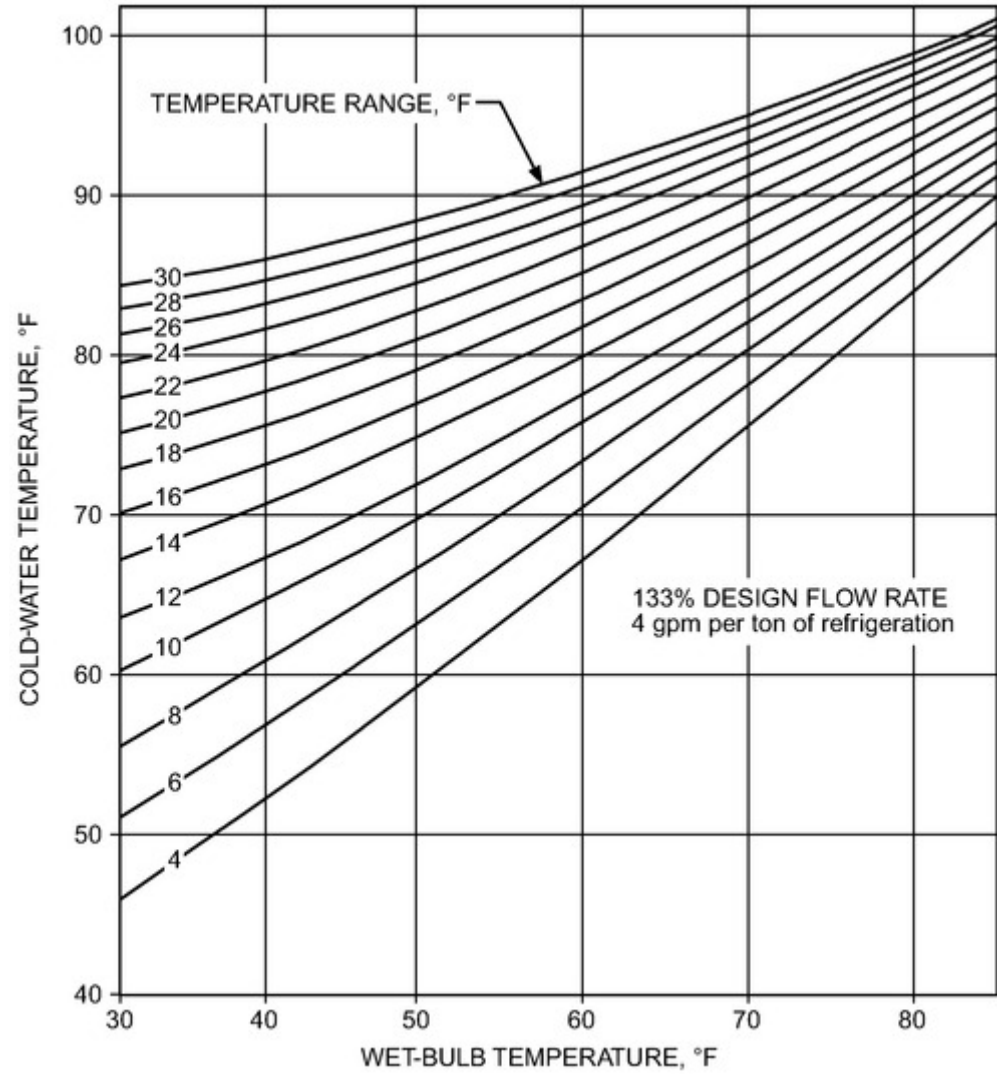


Figure 28. Cooling Tower Performance—133% Design Flow

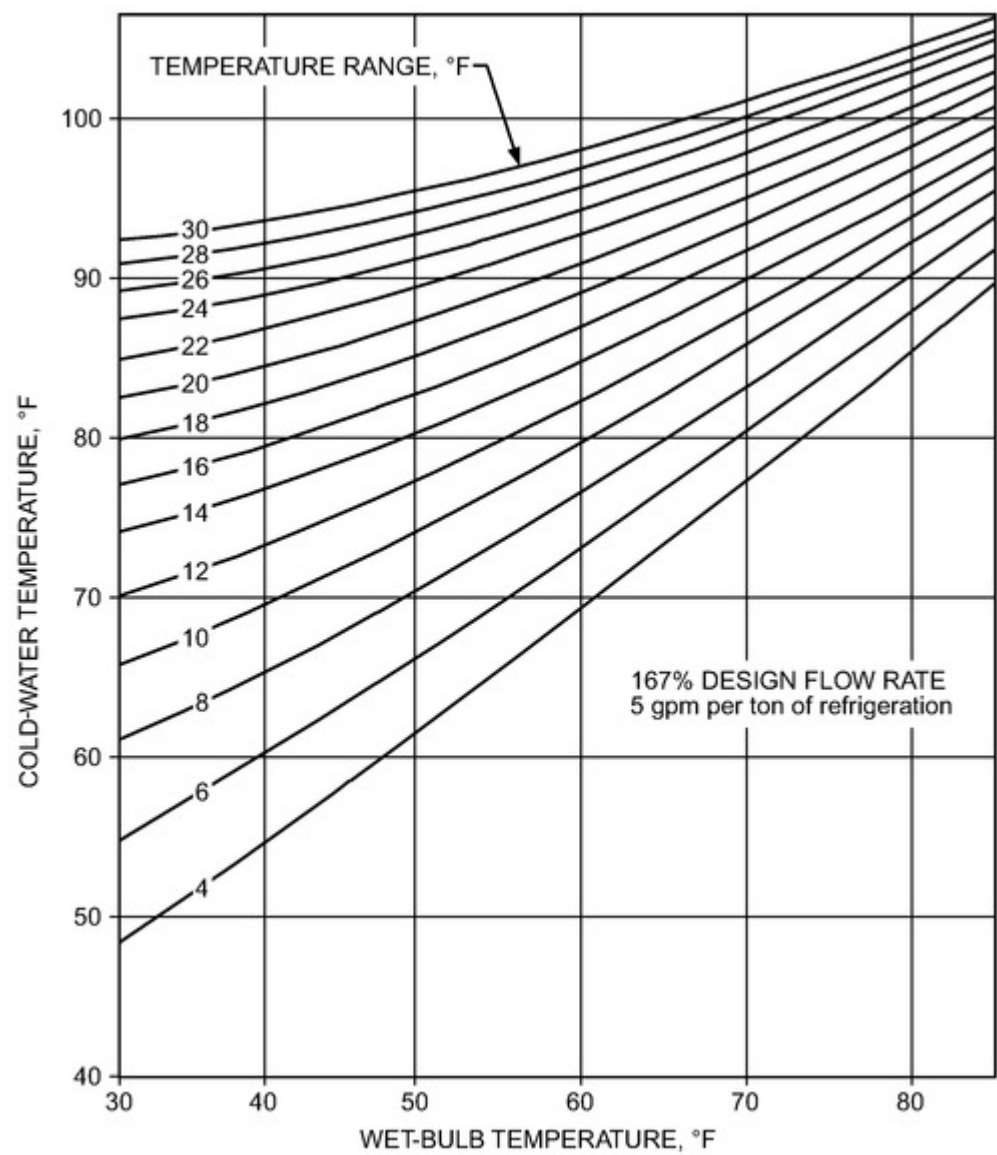


Figure 29. Cooling Tower Performance—167% Design Flow

The format of these curves is similar to the predicted performance curves supplied by manufacturers of cooling towers; the difference is that only three specific ranges (80%, 100%, and 120% of design range) and only three charts are provided, covering 90%, 100%, and 110% of design flow. The curves in [Figures 26 to 29](#), therefore, bracket the acceptable tolerance range of test conditions and may be interpolated for any specific test condition within the scope of the curve families and chart flow rates.

The curves may also be used to identify the feasibility of varying the parameters to meet specific applications. For example, the subject tower can handle a greater heat load (flow rate) when operating in a lower ambient wet-bulb region. This may be seen by comparing the intersection of the 10°F range curve with 73°F wet bulb at 85°F cold water to show the tower is capable of rejecting 33% more heat load at this lower ambient temperature ([Figure 28](#)).

Similar comparisons and cross-plots identify relative cooling tower capacity for a wide range of variables. The curves produce accurate comparisons within the scope of the information presented but should not be extrapolated outside the field of data given. Also, the curves are based on a typical mechanical-draft, film-filled, cross-flow, medium-sized, air-conditioning cooling tower. Other types and sizes of cooling towers produce somewhat different balance points of temperature level. However, the curves may be used to evaluate a tower for year-round or seasonal use if they are restricted to the general operating characteristics described. (See specific manufacturer's data for maximum accuracy when planning for test or critical temperature needs.)

A cooling tower selected for a specified design condition will operate at other temperature levels when the ambient temperature is off-design or when heat load or flow rate varies from the design condition. When flow rate is held constant, range falls as heat load falls, causing temperature levels to fall to a closer approach. Hot- and cold-water temperatures fall when the ambient wet bulb falls at constant heat load, range, and flow rate. As water loading to a particular tower falls at constant ambient wet bulb and range, the tower cools the water to a lower temperature level or closer approach to the wet bulb.

8. COOLING TOWER THERMAL PERFORMANCE

Three basic alternatives are available to a purchaser/designer seeking assurance that a cooling tower will perform as specified: (1) certification of performance by an independent third party such as CTI, (2) an acceptance test performed at the site after the unit is installed, or (3) a performance bond. Codes and standards that pertain to performance certification and field testing of cooling towers are listed in [Chapter 52](#).

Certification - The thermal performance of many commercially available cooling tower lines, both open- and closed-circuit, is certified by CTI in accordance with their *Standard* STD-201, which applies to mechanical-draft, open- and closed-circuit water cooling towers. It is based on entering wet-bulb temperature and certifies cooling tower performance when operating in an open, unrestricted environment. Independent performance certification eliminates the need for field acceptance tests and performance bonds.

Field Acceptance Test. As an alternative to certification, tower performance can be verified after installation by conducting a field acceptance test in accordance with one of the two available test standards. Of the two standards, CTI *Standard* ATC-105 is more commonly used, although American Society of Mechanical Engineers (ASME) *Standard* PTC-23 is also used. CTI *Standard* ATC-105S is used for thermal performance testing of closed-circuit cooling towers. These standards are similar in their requirements, and both base the performance evaluation on entering wet-bulb temperature. ASME *Standard* PTC-23, however, provides an alternative for evaluation based on ambient wet-bulb temperature as well.

With either procedure, the test consists of measuring the hot-water temperature in the inlet piping to the cooling tower or in the hot-water distribution basin. Preferably, the cold-water temperature is measured at the discharge of the circulating pump, where there is much less chance for temperature stratification. The wet-bulb temperature is measured by an array of mechanically aspirated psychrometers. The recirculating water flow rate is measured by any of several approved methods, usually a pitot-tube traverse of the piping leading to the cooling tower. Recently calibrated instruments should be used for all measurements, and electronic data acquisition is recommended for all but the smallest installations.

For an accurate test, the tower should be running under a steady heat load combined with a steady flow of recirculating water, both as near design as possible. Weather conditions should be reasonably stable, with prevailing winds of 10 mph or less. The cooling tower should be clean and adjusted for proper water distribution, with all fans operating at design speed. Both CTI and ASME standards specify maximum recommended deviations from design operating conditions of range, flow, wet-bulb temperature, heat load, and fan power.

9. COOLING TOWER THEORY

Baker and Shryock (1961) developed the following theory. Consider a cooling tower having one square foot of plan area; cooling volume V , containing extended water surface per unit volume a ; and water mass flow rate L and air mass flow rate G . [Figure 30](#) schematically shows the processes of mass and energy transfer. The bulk water at temperature t is surrounded by the bulk air at dry-bulb temperature t_a , having enthalpy h_a and humidity ratio W_a . The interface is assumed to be a film of saturated air with an intermediate temperature t'' , enthalpy h'' , and humidity ratio W'' . Assuming a constant value of 1 Btu/lb·°F for the specific heat of water c_p , the total energy transfer from the water to the interface is

$$dq_w = Lc_p dt = K_L a(t - t'')dV \tag{2}$$

where
 q_w = rate of total heat transfer, bulk water to interface, Btu/h
 L = inlet water mass flow rate, lb/h
 K_L = unit conductance, heat transfer, bulk water to interface, Btu/h·ft²·°F
 V = cooling volume, ft³
 a = area of interface, ft²/ft³
The heat transfer from interface to air is

$$dq_s = K_G a(t'' - t_a)dV \tag{3}$$

where
 q_s = rate of sensible heat transfer, interface to airstream, Btu/h
 K_G = overall unit conductance, sensible heat transfer, interface to main airstream, Btu/h·ft²·°F
The diffusion of water vapor from film to air is

$$dm = K' a(W'' - W_a)dV \tag{4}$$

where
 m = mass transfer rate, interface to airstream, lb/h
 K' = unit conductance, mass transfer, interface to main airstream, lb/h·ft²·(lb/lb)
 W'' = humidity ratio of interface (film), lb/lb
 W_a = humidity ratio of air, lb/lb
The heat transfer caused by evaporation from film to air is

$$dq_L = r dm = rK' a(W'' - W_a)dV \tag{5}$$

where
 q_L = rate of latent heat transfer, interface to airstream, Btu/h
 r = latent heat of evaporation (constant), Btu/lb

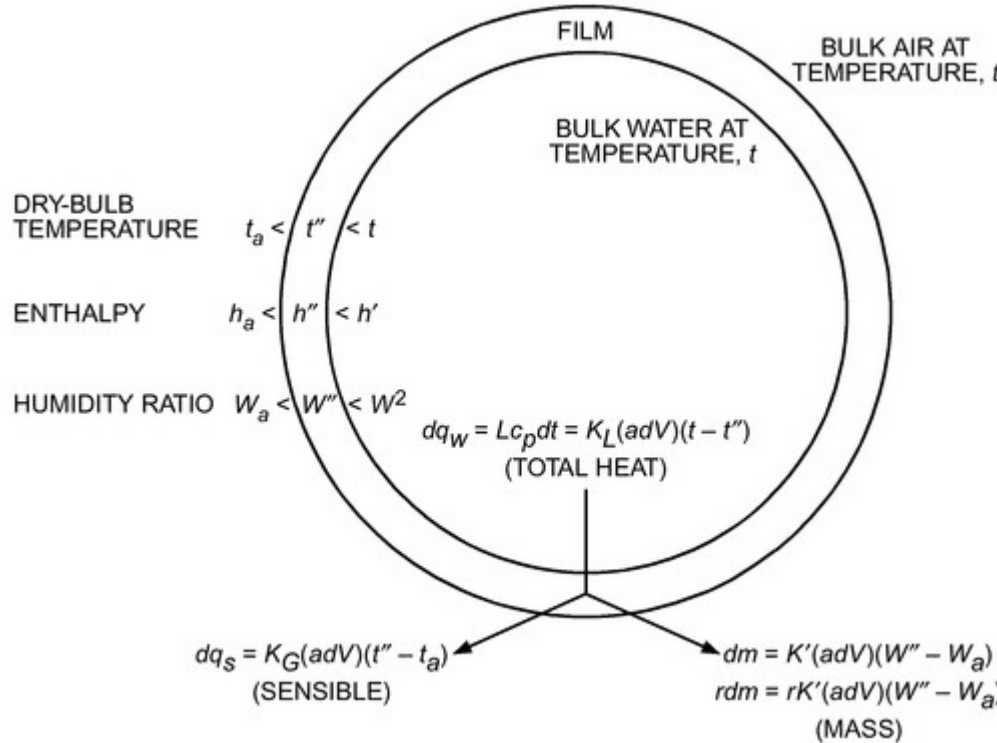


Figure 30. Heat and Mass Transfer Relationships Between Water, Interfacial Film, and Air (Baker and Shryock 1961)

The process reaches equilibrium when $t_a = t$, and the air becomes saturated with moisture at that temperature. Under adiabatic conditions, equilibrium is reached at the temperature of adiabatic saturation or at the thermodynamic wet-bulb temperature of the air. This is the lowest attainable temperature in a cooling tower. The circulating water rapidly approaches this temperature when a tower operates without heat load. The process is the same when a heat load is applied, but the air enthalpy increases as it moves through the tower so the equilibrium temperature increases progressively. The approach of the cooled water to the entering wet-bulb temperature is a function of the tower's capability.

Merkel (1925) assumed the Lewis relationship to be equal to one in combining the transfer of mass and sensible heat into an overall coefficient based on enthalpy difference as the driving force:

$$K_G/(K'c_{pm}) = 1 \tag{6}$$

where c_{pm} is the humid specific heat of moist air in Btu/lb·°F (dry air basis). [Equation \(6\)](#) also explains why the wet-bulb thermometer closely approximates the temperature of adiabatic saturation in an air-water vapor mixture. Setting water heat loss equal to air heat gain yields

$$Lc_p dt = G dh = K' a(h'' - h_a)dV \tag{7}$$

where G is the air mass flow rate in lb/h. The equation considers the transfer from the interface to the airstream, but the interfacial conditions are indeterminate. If the film resistance is neglected and an overall coefficient K' is postulated, based on the driving force of enthalpy h' at the bulk water temperature t , the equation becomes

$$Lc_p dt = G dh = K' a(h' - h_a)dV \tag{8}$$

or

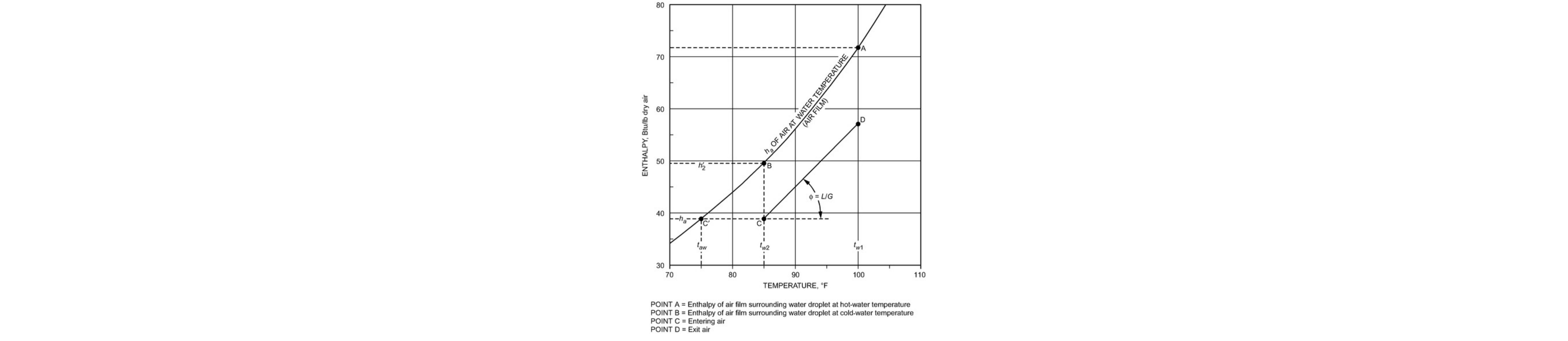
$$K' aV/L = \int_{t_1}^{t_2} \frac{c_p}{h' - h_a} dt \tag{9}$$

and

$$K' aV/G = \int_{h_1}^{h_2} \frac{dh}{h' - h_a} \tag{10}$$

In cooling tower practice, the integrated value of [Equation \(8\)](#) is commonly referred to as the **number of transfer units (NTU)**. This value gives the number of times the average enthalpy potential ($h' - h_a$) goes into the temperature change of the water (Δt) and is a measure of the difficulty of the task. Thus, one transfer unit has the definition of $c_p \Delta t/(h' - h_a)_{av} = 1$. The equations are not self-sufficient and are not subject to direct mathematical solution. They reflect mass and energy balance at any point in a tower and are independent of relative motion of the two fluid streams. Mechanical integration is required to apply the equations, and the procedure must account for relative motion. Integration of [Equation \(8\)](#) gives the NTU for a given set of conditions.

Counterflow Integration
The counterflow cooling diagram is based on the saturation curve for air-water vapor ([Figure 31](#)). As water is cooled from t_{w1} to t_{w2} , the air film enthalpy follows the saturation curve from A to B. Air entering at wet-bulb temperature t_{w2} has an enthalpy h_b corresponding to C'. The initial driving force is the vertical distance BC. Heat removed from the water is added to the air, so the enthalpy increase is proportional to water temperature. The slope of the air operating line CD equals L/G .
Example 1. Air enters the base of a counterflow cooling tower at 75°F wet-bulb temperature, water leaves at 85°F, and L/G (water-to-air ratio) is 1.2, so $d\theta = 1.2 \times 1 \times dt$, where 1 Btu/lb·°F is the specific heat c_p of water. Calculate the NTU for various cooling ranges.
Solution: The calculation is shown in [Table 1](#). Water temperatures are shown in column 1 for 1°F increments from 85 to 90°F and 2°F increments from 90 to 100°F. The corresponding film enthalpies, obtained from psychrometric tables, are shown in column 2.
The upward air path is shown in column 3. The initial air enthalpy is 38.6 Btu/lb, corresponding to a 75°F wet bulb, and increases by the relationship $\Delta h = 1.2 \times 1 \times \Delta t$.
The driving force $h' - h_a$ at each increment is listed in column 4. The reciprocals $1/(h' - h_a)$ are calculated (column 5), Δt is noted (column 6), and the average for each increment is multiplied by $c_p \Delta t$ to obtain the NTU for each increment (column 7). The summation of the incremental values (column 8) represents the NTU for the summation of the incremental temperature changes, which is the cooling range given in column 9.



Because of the slope and position of CD relative to the saturation curve, the potential difference increases progressively from the bottom to the top of the tower in this example. The degree of difficulty decreases as this driving force increases, reflected as a reduction in the incremental NTU proportional to a variation in incremental height. This procedure determines the temperature gradient with respect to cooling tower height.

The procedure of Example 1 considers increments of temperature change and calculates the coincident values of NTU, which correspond to increments of height. Baker and Mart (1952) developed a unit-volume procedure that considers increments of NTU (representing increments of height) with corresponding temperature changes calculated by iteration. The unit-volume procedure is more cumbersome but is necessary in cross-flow integration because it accounts for temperature and enthalpy change, both horizontally and vertically.

Cross-Flow Integration

In a cross-flow tower, water enters at the top; the solid lines of constant water temperature in Figure 32 show its temperature distribution. Air enters from the left, and the dashed lines show constant enthalpies. The cross section is divided into unit volumes in which dV becomes $dx\,dy$ and Equation (7) becomes

$$c_p L\,dt\,dx = G\,dh\,dy = Ka(h' - h_a)dx\,dy \tag{11}$$

The overall L/G ratio applies to each unit volume by considering $dx/dy = w/z$. The cross-sectional shape is automatically considered when an equal number of horizontal and vertical increments are used. Calculations start at the top of the air inlet and proceed down and across. Typical calculations are shown in Figure 33 for water entering at 100°F, air entering at 75°F wet-bulb temperature, and $L/G = 1.0$. Each unit volume represents 0.1 NTU. Temperature change vertically in each unit is determined by iteration from

$$\Delta t = 0.1(h' - h_a)_{avg} \tag{12}$$

The expression $c_p(L/G)dt = dh$ determines the horizontal change in air enthalpy. With each step representing 0.1 NTU, two steps down and across equal 0.2 NTU, etc., for conditions corresponding to the average leaving water temperature.

1		2		3		4		5		6		7		8		9	
Water Temperature t_w , °F		Enthalpy of Film h' , Btu/lb		Enthalpy of Air h_a , Btu/lb		Enthalpy Difference $h' - h_a$, Btu/lb		$\frac{1}{(h' - h_a)}$		Δt , °F		$NTU = \frac{c_p \Delta t}{(h' - h_a)_{avg}}$		ΣNTU		Cumulative Cooling Range, °F	
85		49.4		38.6		10.8		0.0926		1		0.0921		0.0921		1	
86		50.7		39.8		10.9		0.0917		1		0.0917		0.1838		2	
87		51.9		41.0		10.9		0.0917		1		0.0913		0.2751		3	
88		53.2		42.2		11.0		0.0909		1		0.0901		0.3652		4	
89		54.6		43.4		11.2		0.0893		1		0.0889		0.4541		5	
90		55.9		44.6		11.3		0.0885		2		0.1732		0.6273		7	
92		58.8		47.0		11.8		0.0847		2		0.1653		0.7925		9	
94		61.8		49.9		12.4		0.0806		2		0.1569		0.9493		11	
96		64.9		51.8		13.1		0.0763		2		0.1477		1.097		13	
98		68.2		54.2		14.0		0.0714		2		0.1376		1.2346		15	
100		71.7		56.6		15.1		0.0662									

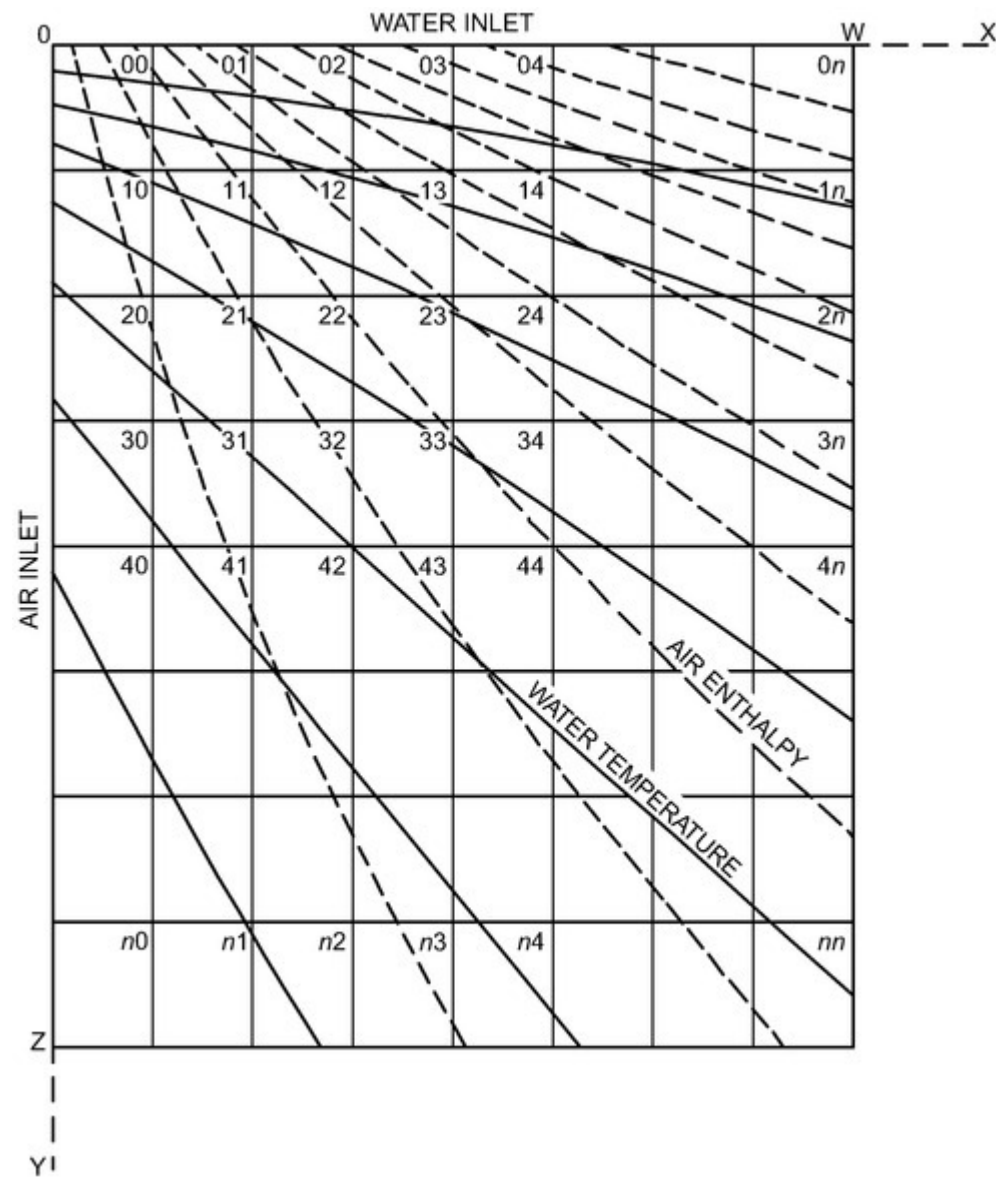


Figure 32. Water Temperature and Air Enthalpy Variation Through Cross-Flow Cooling Tower (Baker and Shryock 1961)

100°F HOT-WATER TEMPERATURE											
71.73 h				71.73 h				71.73 h			
38.59 h _a				38.59 h _a				38.59 h _a			
2.92 M		2.66 M		2.42 M		2.21 M		2.02 M		2.02 M	
97.08°F		97.37°F		97.58°F		97.79°F		98.15°F		98.36°F	
66.68 h		67.11 h		67.52 h		67.87 h		68.20 h		68.20 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
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62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
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2.1		2.2		2.3		2.4		2.5		2.5	
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2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
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62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
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62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
94.59°F		95.07°F		95.45°F		95.82°F		96.19°F		96.56°F	
62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
2.1		2.2		2.3		2.4		2.5		2.5	
2.49 M		2.30 M		2.13 M		1.97 M		1.81 M		1.65 M	
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62.67 h		63.42 h		64.03 h		64.62 h		65.19 h		65.19 h	
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94.59°F		95.07°F									

Calculations can reduce a set of conditions to a numerical value representing degree of difficulty. The NTU corresponding to a set of hypothetical conditions is called the **required coefficient** and evaluates degree of difficulty. When test results are being considered, the NTU represents the available coefficient and becomes an evaluation of the equipment tested.

The calculations consider temperatures and the L/G ratio. The minimum required coefficient for a given set of temperatures occurs at $L/G = 0$, corresponding to an infinite air rate. Air enthalpy does not increase, so the driving force is maximum and the degree of difficulty is minimum. Decreased air rate (increase in L/G) decreases the driving force, and the greater degree of difficulty shows as an increase in NTU. This situation is shown for counterflow in [Figure 35](#). Maximum L/G (minimum air rate) occurs when CD intersects the saturation curve. Driving force becomes zero, and NTU is infinite. The point of zero driving force may occur at the air outlet or at an intermediate point because of the curvature of the saturation curve.

Similar variations occur in cross-flow cooling. Variations in L/G vary the shape of the operating area. At $L/G = 0$, the operating area becomes a horizontal line, which is identical to the counterflow diagram ([Figure 35](#)), and both coefficients are the same. An increase in L/G increases the height of the operating area and decreases the width. This continues as the areas extend to Point A as a limit. This maximum L/G always occurs when the wet-bulb temperature of the air equals the hot-water temperature and not at an intermediate point, as may occur in counterflow.

Both types of flow have the same minimum coefficient at $L/G = 0$, and both increase to infinity at a maximum L/G . The maximums are the same if the counterflow potential reaches zero at the air outlet, but the counterflow tower will have a lower maximum L/G when the potential reaches zero at an intermediate point, as in [Figure 35](#). A cooling tower can be designed to operate at any point within the two limits, but most applications restrict the design to much narrower limits determined by air velocity.

A low air rate requires a large tower, while a high air rate in a smaller tower requires greater fan power. Typical limits in air velocity are about 300 to 700 fpm in counterflow and 350 to 800 fpm or more in cross flow.

Available Coefficients

A cooling tower can operate over a wide range of water rates, air rates, and heat loads, with variation in the approach of the cold water to the wet-bulb temperature. Analysis of a series of test points shows that the available coefficient is not a constant but varies with operating conditions, as shown in [Figure 36](#). [Figure 36](#) is a typical correlation of a tower characteristic showing the variation of available KaV/L with L/G for parameters of constant air velocity. Recent fill developments and more accurate test methods have shown that some of the characteristic lines are curves rather than a series of straight, parallel lines on logarithmic coordinates.

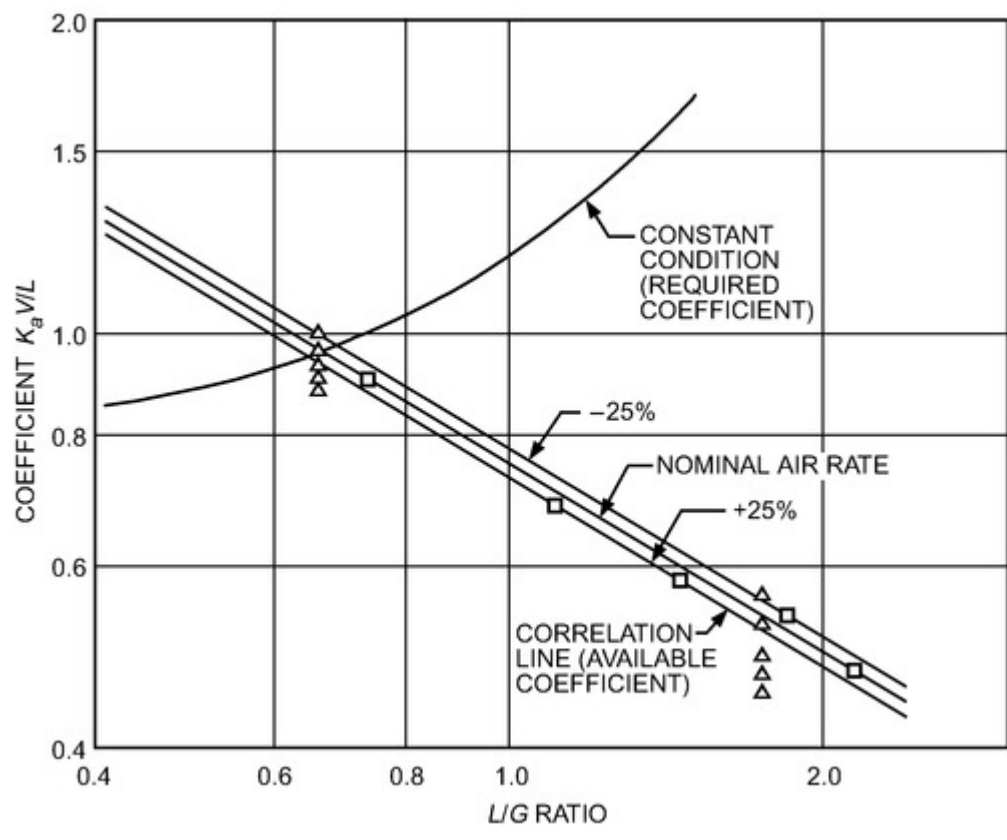


Figure 36. Tower Characteristic, KaV/L Versus L/G (Baker and Shryock 1961)

Ignoring the minor effect of air velocity, a single average curve may be considered:

$$KaV/L \sim (L/G)^n \tag{13}$$

The exponent n varies over a range of about -0.35 to -1.1 but averages between -0.55 and -0.65 . Within the range of testing, -0.6 has been considered sufficiently accurate. The family of curves corresponds to the following relation:

$$KaV/L \sim (L)^n (G)^m \tag{14}$$

where m varies slightly from n numerically and is a positive exponent. The triangular points in [Figure 36](#) show the effect of varying temperature at nominal air rate. The deviations result from simplifying assumptions and may be overcome by modifying the integration procedure. Usual practice, as shown in [Equation \(9\)](#), ignores evaporation and assumes that

$$G \, dh = c_p L \, dt \tag{15}$$

The exact enthalpy rise is greater than this because a portion of the heat in the water stream leaves as vapor in the airstream. The correct heat balance is as follows (Baker and Shryock 1961):

$$G \, dh = c_p L \, dt + c_p L_E (t_{w2} - 32) \tag{16}$$

where L_E is the mass flow rate of water that evaporates, in lb/h. This reduces the driving force and increases the NTU. Evaporation causes the water rate to decrease from L at the inlet to $L - L_E$ at the outlet. The water-to-air ratio varies from L/G at the water inlet to $(L - L_E)/G$ at the outlet. This results in an increased NTU. Basic theory considers the transfer from the interface to the airstream. As the film conditions are indeterminate, film resistance is neglected as assumed in [Equation \(7\)](#). The resulting coefficients show deviations closely associated with hot-water temperature and may be modified by an empirical hot-water correction factor (Baker and Mart 1952). The effect of film resistance (Mickley 1949) is shown in [Figure 37](#). Water at temperature t is assumed to be surrounded by a film of saturated air at the same temperature at enthalpy h' (Point B on the saturation curve). The film is actually at a lower temperature t'' at enthalpy h'' (Point B'). The surrounding air at enthalpy h_a corresponds to Point C. The apparent potential difference is commonly considered to be $h' - h_a$, but the true potential difference is $h'' - h_a$ (Mickley 1949). From [Equations \(11\) and \(6\)](#),



Figure 37. True Versus Apparent Potential Difference (Baker and Shryock 1961)

The slope of CB' is the ratio of the two coefficients. No means to evaluate the coefficients has been proposed, but a slope of -11.1 for cross-flow towers has been reported (Baker and Shryock 1961).

Establishing Tower Characteristics

The performance characteristic of a fill pattern can vary widely because of several external factors. For a given volume of fill, the optimal thermal performance is obtained with uniform air and water distribution throughout the fill pack. Irregularities in either alter the local L/G ratios within the pack and adversely affect the overall thermal performance of the cooling tower. Accordingly, the design of the cooling tower water distribution system, air inlets, fan plenum, and so forth is very important in ensuring that the tower performs to its potential.

In counterflow towers, some cooling occurs in the spray chamber above the fill and in the open space below the fill. This additional performance is erroneously attributed to the fill itself, which can lead to inaccurate predictions of a cooling tower's performance in other applications. A true performance characteristic for the total cooling tower can only be developed from full-scale tests of the actual cooling tower assembly, typically by the tower manufacturer, and not by combining performance data of individual components.

11. ADDITIONAL INFORMATION

The Cooling Technology Institute (CTI) (www.cti.org) offers a reference guide on CD-ROM containing information on psychrometrics, Merkel KaV/L calculation, characteristic curve performance evaluation, and performance curve evaluation, along with general information on cooling towers of all types.

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