PDHonline Course M375 (4 PDH)

Heat Rejection Options in HVAC Systems

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2020

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Abstract

Air conditioning systems captures the heat energy from within the environment and rejects it to the environment using air or water as the medium. Where there is an available, relatively inexpensive water supply, the typical equipment used is a wet cooling tower. The cooling tower circulates water to the shell and tube condenser, where the water absorbs heat from the condensing refrigerant and is then returned to the cooling tower where it falls through a media while subjected to a cross-flow or counter-flow current of ambient air, forced or induced through the cooling tower by a fan. Other condenser cooling/heat rejection options include evaporative cooling, which is similar to the cooling tower process, except evaporating water is used directly to cool the condenser.

If water is not available or if the cooling system operates on a minimal number of hours, heat rejection can be accomplished with ambient air using a finned coil condenser. A typical air cooled condenser has the hot, high-pressure refrigerant vapor flowing through the tubes of a finned-tube heat exchanger and uses propeller-type fans to draw outdoor air over the outer surfaces of the tubes and fins.

In order to properly apply the heat rejection concepts, HVAC designer must be aware of the different heat rejection methods. In this course we will discuss the various heat rejection methods as well the controls that may be used to maintain proper refrigerant and water temperatures. Also presented in the course is the concept of total heat of rejection, its derivation and how it applies to the process of air conditioning. The course is divided into 7- sections:

PART -1	Methods of Heat Rejection
PART- 2	Air-Cooled Condensers
PART -3	Cooling Towers
PART- 4	Closed Circuit Fluid Coolers
PART -5	Evaporative Condensers
PART- 6	Adiabatic Condensers
PART- 7	Selecting the Right System

PART -1 METHODS OF HEAT REJECTION

There are five prominent ways of heat rejection:

1. Air cooled condensing units
2. Closed circuit coolers
3. Evaporative condensers
4. Cooling Towers
5. Adiabatic condensers

Background

It is important to understand "what heat of rejection is" before discussing the selection of appropriate method, equipment or technology.

Heat of rejection is the energy removed from a refrigerant in the condensing process. Hot gaseous refrigerant enters the condenser where it loses its latent heat of evaporation to become hot liquid refrigerant. That process occurs regardless of the method adopted to absorb the heat rejected.

In typical terms the heat of rejection is some 15% to 25% **greater** than the cooling effect in the evaporator. This is because the heat of compression is added into the system. The actual percentage that occurs depends upon a number of factors including the suction temperature and the discharge temperature. Low suction temperature and/or high discharge temperature increases the percentage. As an example: Standard selection for reciprocating compressor operating on HCFC-22 is usually 40°F saturated suction and 105°F condensing temperature. The heat of compression at this condition is typically 18.6%. If the same compressor operates at 40°F saturated suction and 120°F condensing temperature, the heat of compression shall be 23.6% and if it operates at 30°F saturated suction and 105°F condensing temperature, the heat of compression shall be 21.8%. The selection of refrigerant has little impact upon the percentage result.

Further factors in the control of a refrigeration system are superheat and sub-cooling.

Superheat is the "extra" heat added to the refrigerant vapor beyond what is required to vaporize all of the liquid. Superheating ensures total evaporation of the liquid refrigerant before it goes into the compressor. While some amount of superheat is required to protect the refrigeration system and prevent liquid entering the compressor, too much superheat can cause high operating temperature at compressor and consequent oil breakdown and increased system downtime. Super heat also contributes to increase in the total heat of reject at the condenser and it should be in the order of 5.5°F for system protection.

Sub-cooling is the process of cooling condensed gas beyond what is required for the condensation process. Sub-cooling can have a dramatic effect on the capacity of a refrigeration system - as a general rule; a 1% increase in refrigeration capacity can be achieved for every 2 degrees of liquid sub-cooling. Due to this characteristic, designs of condensers have been changed to achieve liquid sub-cooling. Sub-cooling is best accomplished in a separate sub-cooler or a special sub-cooling section of a condenser because tube surface must be submerged in liquid refrigerant for sub-cooling to occur. In an air cooled, adiabatic and evaporative condenser, a secondary coil is used to achieve the sub-cooling. A good sub-cooling is about 10°F.

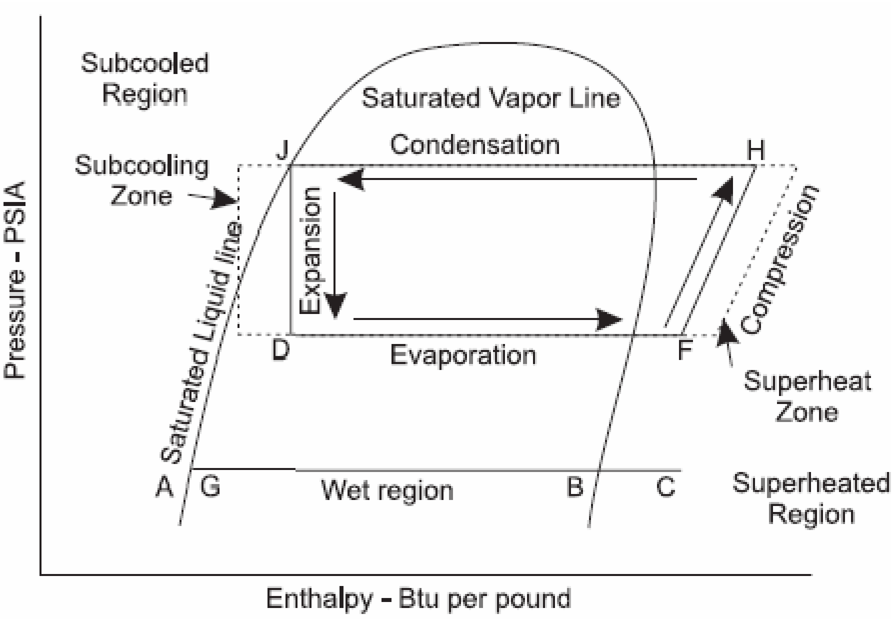
Condensing Temperature: The condensing temperature is the temperature at which the refrigerant gas will condense to a liquid, at a given pressure. It should not be confused with the discharge temperature, which is the temperature when the superheated gas leaves the compressor. Air cooled condensers normally requires between 125°F to 130°F condensing temperature to reject heat to a 100° ambient, while a water cooled condenser can operate at 105°F condensing temperature and reject its heat to a 95°F water stream. The discharge temperature is of the order of 165° and is not the same as the condensing temperature although the pressure is the same.

Condensers are rated in terms of total heat rejection (THR), which is the total heat removed in de-superheating, condensing and sub-cooling the refrigerant.

Condenser Total Heat of Rejection (THR)

Total heat of rejection (THR) is equal to net refrigeration effect (RE) at the evaporator (compressor capacity) plus the energy input into the refrigerant by the compressor (heat of compression). The heat of compression will vary depending on the compressor manufacturer, type of compressor and the operating conditions of the compressor.

Heat rejection in the condenser may be illustrated on the P-H (pressure – enthalpy) diagram. A pressure enthalpy diagram is used because condensing takes place at constant pressure or nearly constant pressure when blended refrigerants are used.



The THR of the condenser is defined by line J-H, which is the sum of the refrigeration effect (line D-F) and the heat of compression line F-H. As the ratio between compressor discharge and suction pressure increase, the refrigerant effect decreases and the heat of compression increases. This is because the work done by the compressor has increased.

THR Equations:

In cases where the brake horsepower (BHP) of the compressor is known:

THR = RE + (BHP * 2545)

- RE is the refrigeration effect or the compressor capacity in Btuh
- 2545 is a constant; it is the Btuh equivalent of one BHP
- Btuh is the application rating for the compressor

In cases where the compressor kW is known:

THR = RE + (kW * 3414)

- RE is the refrigeration effect or the compressor capacity in Btuh
- 3414 is equivalent of one kW

If you don't know the compressor energy consumption:

THR = RE * Heat Rejection Factor

What is the heat rejection factor?

Heat rejection factor is a multiplier obtained from the compressor manufacturer to calculate the condenser rating.

The amount of heat added to the cooling capacity to arrive at the THR for any given application is a function of the compressor efficiency and the condenser cooling method (air, water or evaporative) cooled. The compressors used in HVAC equipment typically have a full load heat rejection factor in the range of 1.15 to 1.25.

Water cooled screw and centrifugal compressors are very efficient, so they tend to have heat rejection factors between 1.15 and 1.18. Compressors used in air cooled applications typically have heat rejection factors closer to 1.25. This efficiency is a function of the standard condensing temperature, which is lower for water cooled chiller compressors.

Using a value of 1.17 as an example for a water cooled chiller, for every ton (12000 Btuh) refrigeration effect, the load on the water cooled condenser would be:

12000 * 1.17 = 14040 Btuh heat rejection for each ton of cooling capacity

A heat rejection factor of 1.25 results in 15000 Btuh heat rejection per ton of cooling. (12000 * 1.25 = 15,000)

Note that:

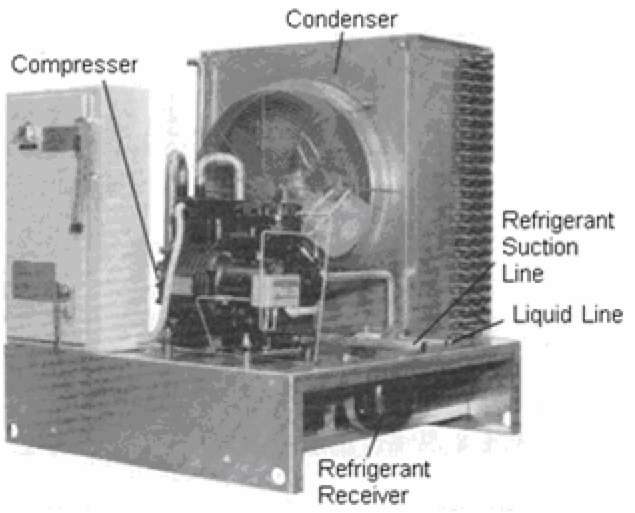
- THR can be expressed in Btuh, tons or MBtuh. One MBtuh is equal to 1000 Btuh.

- Most DX systems employ hermetic /semi-hermetic compressors where the compressor motor is contained within the compressor housing and the motor cooling is achieved by the refrigerant. As the motor is cooled, the heat energy is passed to the refrigerant vapor, which must be rejected at the condenser. Condensers for hermetic / semi-hermetic systems are therefore slightly larger than for open-drive systems where the motor is itself air-cooled.
- The water cooled systems benefits from the lower condensing temperatures. In water cooled system, all refrigeration system impacts are encompassed in the chiller condensing unit, so the designer is not concerned with factors such as superheat and sub-cooling. The term superheat and sub-cooling is more relevant to air cooled heat rejection equipment.

PART- 2 AIR COOLED CONDENSERS

As the name suggests, the air-cooled condensers use ambient air to extract the sensible heat and latent heat released by the refrigerant during condensation. At the air cooled condensing unit, the refrigerant is forced by the compressor through smaller copper tubes which have thin aluminum fins mechanically bonded to them. Ambient air is then forced through the condenser coil by the fan(s). This causes the hot refrigerant gas to condense into a liquid, changing state, and releasing the heat that the gas collected at the chiller evaporator. The waste heat is carried away into the ambient air by the fans. The liquid is then forced through the orifice and the process starts again.

Compared to water, air is a poor conductor of heat and therefore air-cooled condensing units are larger and less efficient. Air-cooled condensers normally operate with a temperature difference (TD) of 10 to 30°F between the refrigerant and the ambient air. As the ambient air temperature increases, the condensing temperature increases and net cooling capacity decreases by about 2% for every 5°F increase in condensing temperature. The typical condensing temperature for an air-cooled chiller is 120°F as opposed to a 105°F in a comparable water condensed chiller.



AIR COOLED CONDENSING UNIT

Types & Description of Air- Cooled Condensers

Air-cooled condensers come in a wide variety of shapes and sizes, square or rectangular, flat or bent, in capacities of a few BTUH to hundreds of thousands. These can be coupled with the compressor and evaporator in a packaged air-cooled chiller or can be located remotely. Remote air-cooled condensers are usually located outdoors and have propeller fans and finned refrigerant coils housed in a weatherproof casing.

The most commonly used fans are axial flow or propeller fans, which are capable of moving large volumes of air, while consuming only 0.08 to 0.15 kW per ton of refrigeration. Since, these fans develop low static pressure of 6 to 10 mm (water gauge), condenser coils are designed with a large face area, but with fewer rows to minimize the resistance to air flow offered by the coil. The condenser coils used with small and medium split system air-conditioners have a relatively large face area and only 1 or 2 rows. This enables the use of low static pressure, low power and hence less expensive fans. Also, the row "effectiveness" or contribution of each succeeding row falls off progressively for every additional row. Hence, limiting the number of rows yields a cost-effective coil design.

Figure: Remote Air-Cooled Condenser

Condenser air flows lie in the region of 600 to 1000 cfm per ton at face velocities of 400 to 800 fpm. Centrifugal fans, which are capable of developing higher static pressure, are occasionally used with air-cooled condensers which have to be located indoors or in the basement, so that the hot discharge air off the condenser coil can be ducted out.

Air-cooled condensers are designed for either draw thru' or blow thru' air flow. Both types have their pros and cons. With draw thru' design, the face velocity across the coil is more uniform and the coil is more effectively utilized. However, the hot discharge air off the condenser coil flows over the fan and the drive motor, which have to withstand the hot air temperature. In blow thru' designs, the fan and drive motor have ambient air flowing over them. But the face velocity across the coil is less uniform than in the draw thru' design.

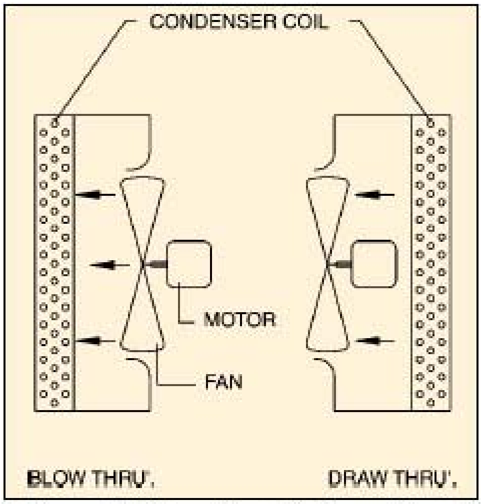


Figure: Blow Thru & Draw thru Condenser

APPLICATIONS

Air cooled chillers are more often used in smaller chiller plants, (generally below 200 tons), as space, water treatment and the additional maintenance cost associated with cooling towers or evaporative condensers outweighs the energy benefit.

Noise is important parameter particularly in larger units having multiple fans. It is desirable to use large diameter, low speed fans to reduce fan noise.

RATINGS & SELECTION

Condensers are rated in terms of total heat rejection (THR), which is the energy absorbed at the evaporator plus the work input to the compressor. The THR is also the product of the refrigerant mass flow and the enthalpy difference between the refrigerant vapor entering and refrigerant liquid leaving the condenser coil.

Condensers are also frequently rated in terms of net refrigerating effect (NRE), assuming a certain heat rejection factor depending on whether the compressor is an open type or hermetic.

In an air-cooled condenser, the refrigerant looses heat by de-superheating, condensing and sub-cooling. The de-superheating and sub-cooling zones occupy 5 to 10% each of the condensing surface area, depending on the entering superheated refrigerant vapor and the leaving refrigerant liquid temperatures. The "condensing" zone occupies 80 to 85% of the coil area (Figure below). Some condenser coils are provided with integral sub-cooling passes at the bottom of the coil to enhance sub-cooling. Overall system capacity increases about 0.5% for every degree F sub-cooling at the same suction and discharge pressures.

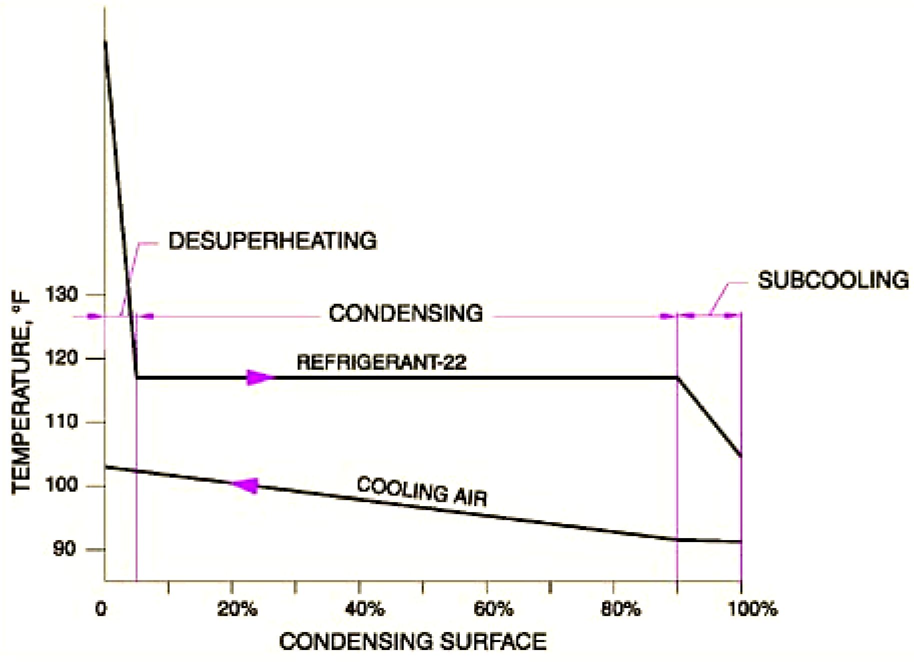


Figure: Typical Temperature curve for refrigerant (R-22) and Cooling Air in an Air Cooled Condenser

The total heat rejection capacity of an air-cooled condenser is proportional to the condenser temperature difference (TD), which is defined as the difference in saturated condensing temperature (corresponding to the refrigerant pressure at the inlet) and the air intake dry bulb temperature. Air-cooled condensers are rated at a specific TD related to the evaporating temperature of the refrigeration system. Typical TD values are 20° to 30°F for high temperature systems (air-conditioning applications), 15°to 20°F for medium temperature systems (such as water coolers) and 10°to 15°F for low temperature applications (refrigerators and freezers).

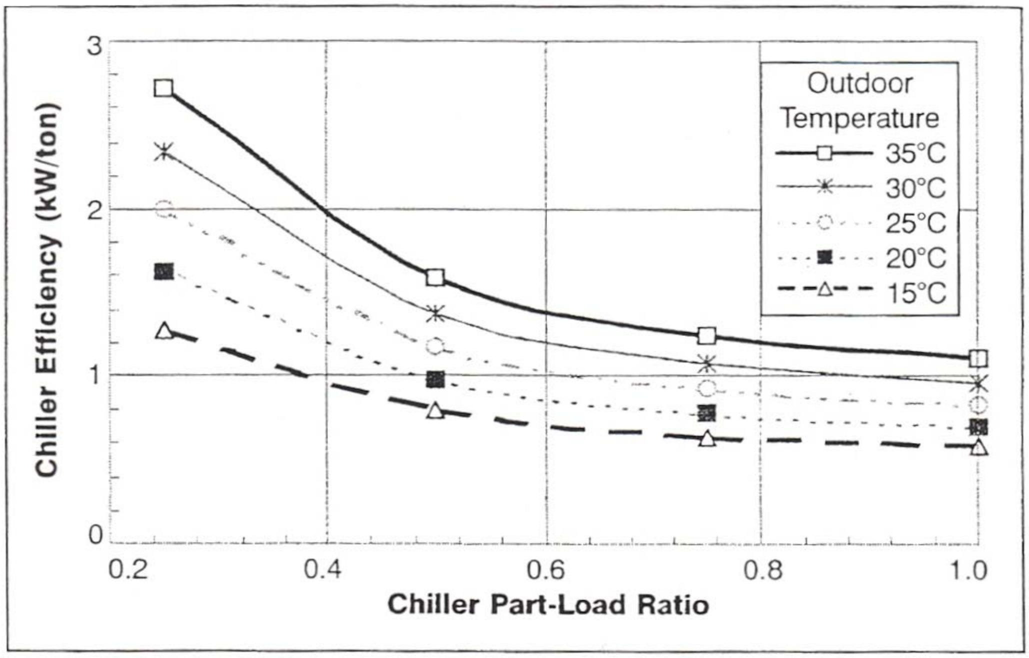
Maximum **size** for remote air-cooled refrigerant condensers is about 500 tons, with 250-ton maximum being more common.

AIR- COOLED CHILLER PERFORMANCE

The energy efficiency of air-cooled chillers is frequently reported as the Energy Efficiency Ratio, EER. EER includes the electrical power for both the compressor and condenser fans.

EER (Btu/Wh) = Evaporator Load (Btu/hr) / [$W_{compressor}$ (watts) + $W_{condenser\ fans}$ (watts)]

Performance data from typical air-cooled chillers are shown below. The data show that energy efficiency decreases at part-loads and high outdoor air temperatures.



INSTALLATION

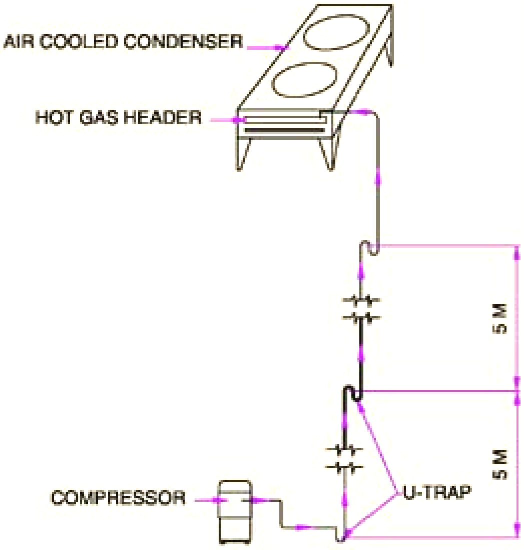
Air-cooled condensers should be installed in such a way that there is no obstruction or resistance to air flow either on the air intake or on the air discharge side. The condenser should not be placed too close to a wall or a ceiling which might obstruct or affect the air flow through the condenser. The air discharging from the condenser should also not "short cycle" or get partly sucked back into the condenser along with the entering air. The obstruction on the discharge side is more critical and should be much farther away since the condenser fan should not "see" any additional resistance to air flow because of the obstruction.

Air-cooled condensers with propeller fans should never be ducted to discharge the hot air off the condenser. Since propeller fans develop low static pressure, the resistance offered by the discharge duct will severely restrict the air flow from the fan and starve the condenser of cooling air.

Designing the piping for remote air-cooled condenser application is somewhat tricky. Care must be taken to properly size the hot gas line to limit pressure drop and to assure that the oil carried by the refrigerant does not accumulate in the piping. The minimum oil carrying capacity of the hot gas piping needs to account for the lowest load (considering compressor unloading).

If the condenser is located below the evaporator, the liquid line must be carefully sized to prevent flashing caused by the pressure drop not only by the pipe friction but also by the change in elevation of the fluid. Additional sub-cooling may be required in this instance. When the condenser is located above the compressor, care must be taken to prevent the liquid refrigerant and oil from flowing backward by gravity into the compressor. This usually means that the hot gas line runs to the floor before rising and that there is a check valve at the top just upstream of the condenser.

When the air-cooled condenser of a packaged air-conditioner or compressor-cooler unit is installed on the rooftop (or several floors above the indoor unit), the following precautions should be taken to prevent the possibility of compressor failure:



The compressor discharge line should be bent down to the floor of the unit before routing it upwards towards the condenser. Similarly, the vertical discharge riser from the compressor should be looped above the air-cooled condenser before entering it. If this is not done, the refrigerant in the vertical discharge riser or the hot gas header (of the condenser) may condense during the off-cycle and collect on the compressor discharge valve and seep into the cylinder. When the compressor restarts, it will try to compress refrigerant liquid (instead of vapor), resulting in possible mechanical failure.

A 'U' trap should be provided in the compressor discharge line near the compressor at the bottom of the discharge riser and at every 5 meters height. These 'U' traps collect condensed refrigerant and oil and prevent them from reaching the compressor discharge valve. As an additional precaution, a discharge line check valve may be provided in the discharge line near the compressor.

Other specific design good practices include:

- There must be a liquid receiver with every air cooled condenser. If there is no receiver the refrigerant charge is considered critical; meaning the amount of refrigerant in the system must be exact;
- The pipe line carrying refrigerant from the condenser to the receiver is not a liquid line. It is a condensate line that must be larger than a liquid line so the liquid can drain out of the condenser into the receiver. Consequently the receiver must be below the condenser by a considerable distance;
- A separate sub-cooling coil should be fitted to every condenser to ensure the liquid flow from the condenser to the hot liquid side is stable. A liquid line leaves the bottom of the receiver and runs to the sub-cooling coil and then to the expansion device;
- Flash gas will form in the top of the receiver so it must vent though a small valved line to the top of the discharge (hot gas) line before it enters the condenser.

CONTROLS

At low ambient temperatures or under part-load operation, the compressor discharge or head pressure may become too low, which may cause the expansion valve to malfunction. Hence the discharge pressure needs to be artificially raised using suitable control sequence. These controls include:

- **Fan cycling:** Usually need multiple fans with one or more cycling on and off to maintain minimum head pressure.
- **Dampers:** Discharge dampers on condenser fan restrict airflow.

- **Variable-speed fans:** Fan speed modulates airflow.
- **Flooded coil:** Control valves back up liquid refrigerant into the condenser to limit the heat transfer surface. This requires a receiver and a large refrigerant charge.

For systems intended to run at temperatures above 40°F, fan cycling is usually the most appropriate choice for control. For systems intended to run at temperatures less than 40°F down to 0°F, fan speed control or dampers use is recommended.

OPERATION & MAINTENANCE

In operation, condenser coils get fouled up by dust, lint or grease from a dirty environment or nearby machinery in operation. An excessive fouling up of the condenser coils will raise the operating discharge pressure and may increase compressor power consumption by up to 30%. Simultaneously, there is a loss of cooling capacity, which means that the compressor has to run for longer periods to produce the same cooling.

Coils must be periodically cleaned. If the buildup of dirt, lint or grease is light, the coils may be cleaned by a brush, vacuum cleaner or compressed air. In case of heavier buildup, it may be necessary to use a mild detergent or cleaning solution. While cleaning, care should be taken to prevent deforming or damaging the condenser fins which might block airflow through the coil and compound the original problem.

Benefits

- Air-cooled condensers are cooled by ambient air and no water is required as the cooling medium. This is a big advantage in regions where water is scarce;
- Air-cooled condensers have less operational problems such as trapping of oil and require a relatively small quantity of refrigerant in the system in comparison to shell and tube water cooled condenser systems;
- Air-cooled condensers do not need machine rooms with safety monitoring, venting etc;
- Air cooled condensers are NOT prone to Legionella risk.

Limitations

- Air-cooled condensers operate at a greater condensing temperature than water cooled condensers; hence the compressor (and the refrigeration system) delivers

15 to 20% lower capacity. Therefore one has to use a larger compressor. At the same time, the compressor consumes greater power;

- The largest air cooled condenser available in a packaged range is 250 TR. This equates to the cooling effects to roughly 200 TR (assuming 25% heat of compression). The foot print for a horizontal unit of this size shall be roughly 7.5m x 2.4m with an access need of 1.2M all around;
- Propeller fan(s) used in the condensing unit can be noisy and may require special precautions depending on the application. The manufacturer's technical data will normally quote the noise level generated by each product. It must be remembered that where two or more air cooled condensers are sited in close proximity that the cumulative sound levels will be greater than that of a single unit;
- In corrosive or salty environments, the aluminum fins are virtually "eaten" away over a period of time. One remedy is to use all copper coils, which may be further tinned to enhance their corrosion resistance. Copper will give marginally better performance but at significantly greater cost. A cheaper alternative is to use epoxy or vinyl coated aluminum fins. A more expensive method is to give a baked epoxy coat over the entire coil. One such patented process is known as "Heresiting". Several proprietary chemical sprays are also available; these may be sprayed over the condenser coil at site and provide some degree of corrosion protection.

PART -3 COOLING TOWERS

A cooling tower is a heat exchanger, where heat is withdrawn from the water by contact between the water and the air. The heat transfer occurs through the heat exchange between air and water and through the evaporation of a small part of the water that needs to be cooled. This will allow to cool down to a temperature lower than the ambient temperature, which is an important advantage compared to dry air cooled condensers.

In a cooling tower, approximately 1% of the total flow is evaporated for each 12.5°F temperature change. There are several important terms used in the discussion of cooling towers:

- **Range:** The temperature difference between the water entering the cooling tower and the temperature leaving the tower.
- **Approach:** The temperature difference between the water leaving the cooling tower and the ambient wet-bulb temperature.
- **Heat load:** A ton of air-conditioning is the rejection of 12,000 Btu/hour. The equivalent ton on the cooling tower is about 15,000 Btu/hour due to the heat-equivalent of the energy needed to drive the chiller's compressor.

The performance of a cooling tower is a function of the ambient wet-bulb temperature, entering water temperature, air flow and water flow. Water-cooled chillers are normally more energy efficient than air-cooled chillers due to heat rejection at near wet-bulb temperatures. The dry-bulb temperature has an insignificant effect on the performance of a cooling tower. Air-cooled chillers must reject heat to the dry-bulb temperature, and thus have lower average reverse-Carnot cycle effectiveness.

TYPES OF COOLING TOWERS

Cooling towers can be divided into types in different ways: based on the fan type, shape, water flow or efficiency, cooling water quality ... The main classification tends to be based on the cooling circuit type, which determines the exact operation of the cooling tower.

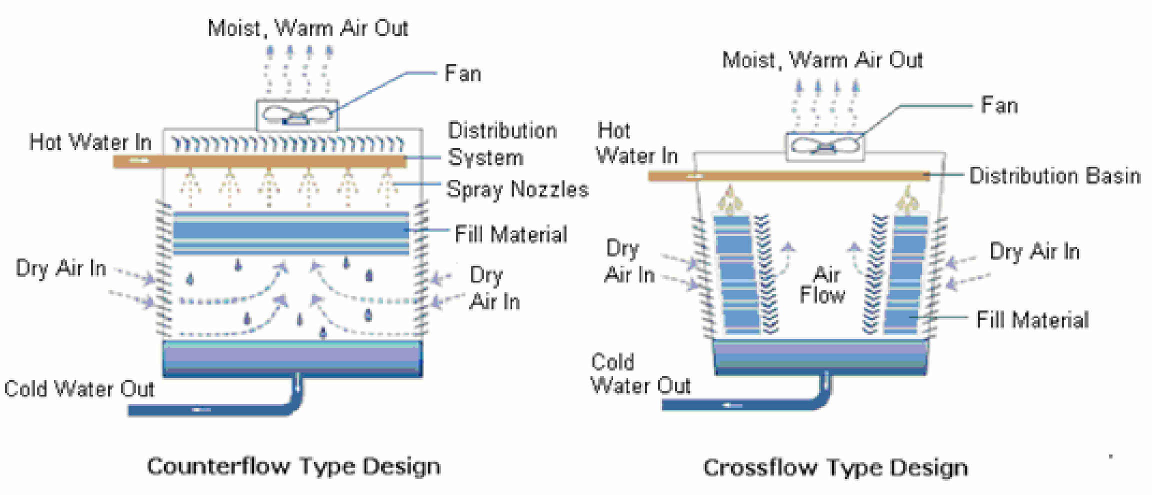
One way to distinguish between cooling towers is how the air and water interact, open cooling towers or closed cooling towers. Open cooling towers, also called direct cooling towers, allow the water to come into contact with outside air. Closed loop (or closed circuit) cooling tower systems, also called indirect cooling tower systems, do not allow the water to come into contact with any outside substance, therefore keeping the water more pure due to the lack of foreign particles introduced.

Another classification of cooling towers is made on the fan configuration and arrangement. The tower airflow can be driven by a fan (mechanical draft) or can be induced by a high pressure water spray. The mechanical draft units can blow the air through the tower (forced draft) or can pull the air through the tower (induced draft). Forced draught towers are characterized by high air entrance velocities and low exit velocities, which can make them susceptible to recirculation, giving instability in performance.

The water invariably flows vertically from the top down, but the air can be moved horizontally through the water (cross-flow) or can be drawn vertically upward against the flow (counter-flow). In counter-flow towers, the water and air flow in opposite directions, i.e. the water flows vertically downward and the air flows vertically upward. In cross-flow towers, the two flow streams are arranged at 90° to each other, i.e., the water flows vertically downward through the fill, while the air flows horizontally through it.

- **Cross-flow** towers are the better selection when it is desirable to minimize tower fan energy consumption, minimize pump size and pumping energy. Cross-flow designs, typically with relatively large fan plenums and externally accessible gravity water distribution systems, offer excellent features in terms of maintenance and access to critical tower components relative to other designs.

- The **counter-flow** tower is the better selection where the available space (footprint) is limited and/or where icing during winter operation is a concern. But these tend to be taller than their cross-flow counterparts, resulting in increased pump head, which translates to higher pump energy as well as the requirement for taller architectural screens. Counter-flow towers also use pressurized spray systems typically not accessible for inspection without shutting down the tower. Counter-flow towers are typically expensive to build and have higher capital cost compared to cross-flow tower.



TYPES OF COOLING TOWER

Water surface area is increased by using "fill." Fill can be "splash-type" or "film-type."

- **Film-type** fill is most commonly used and consists of closely spaced sheets of PVC arranged vertically.
- **Splash-type** fill uses bars to break up the water as it cascades through staggered rows.

Typically, in the HVAC industry, cooling towers are "packaged" towers that are factory fabricated and shipped intact to a site.

"Field-erected" towers mostly serve very large chiller plants and industrial/utility projects. When aesthetics play a role in the selection of the type of tower, custom designed field-erected cooling towers are sometimes used. In these towers, the splash-type fill is often made of ceramic or concrete blocks. Larger cell sizes coupled with improved fill designs can produce capacities as high as 1,350 nominal tons in a single factory-assembled cell. These larger cells shorten tower installation schedules and reduce the uncertainty due to weather, labor issues, etc. associated with field-erected towers. Field erected towers are not often used in HVAC applications.

Forced Draft Cooling Towers

Forced draft towers can be of the cross-flow or counter-flow type, with axial or centrifugal fans. The forward curved centrifugal fan is commonly used in forced draft cooling towers. The primary advantage of the centrifugal fan is that it has capability to overcome high static pressures that might be encountered if the tower were located within a building or if sound traps were located on the inlet and/or outlet of the tower. Cross-flow towers with centrifugal fans are also used where low profile towers are needed. These towers are relatively quieter than other types of towers. Forced draft towers with centrifugal fans are not energy efficient. The energy to operate this tower is more than twice that required for a tower with an axial fan. Another disadvantage of the forced draft tower is that, because of low discharge air velocities, they are more susceptible to recirculation than an induced draft tower.

Induced Draft Cooling Towers

The induced draft tower is by far the most widely used and energy-efficient cooling tower available in the HVAC industry. These towers can be cross-flow or counter-flow and use axial fans. Induced draught towers have an air discharge velocity of from 3 - 4 times higher than their air entrance velocity, and the location of the fan in the warm air exit stream provides excellent protection against the formulation of ice on the mechanical components. Because the air discharges at a high velocity, they are not as susceptible to recirculation. The large blades of the axial fan can create noise at low frequencies that is difficult to attenuate and, depending on the location on the property, could cause problems. The axial fans have either a belt drive or direct (shaft) drive. Direct drive fans use gear reducers to maintain the low speeds of the fan. Belt drive towers have the disadvantage that the motor and belts are located within the moist air stream of the tower exhaust, making them more susceptible to corrosion and fouling and more difficult to maintain. Belt drive towers usually cost less than towers with direct drives.

Induced draught towers can be used on installations as small as 20 gallons per minute (GPM) and to as high as 2500 GPM.

COOLING TOWER SELECTION

In HVAC applications, the starting place for cooling towers selection is typically to match the “nominal cooling tower tons”, as supplied by the tower manufacturer, to the cooling capacity of the chiller or chiller plant. A **“nominal cooling tower ton”** is defined as cooling 3 gpm of water from 95°F to 85°F at an air wet-bulb temperature of 78°F. Thus, the actual cooling associated with a “nominal cooling tower ton” is:

Q actual = 3 gpm x 8.33 lb/gal x 60 min/hr x 1 Btu/lb F x (95 – 85) F = 15,000 Btu/hr

This strange convention exists to make it easy for users to select cooling towers by matching the “nominal cooling capacity” of the chiller with the chiller cooling capacity.

The convention works because most chillers have a COP of about 3, and total heat rejected by the condenser to the cooling tower is about 15,000 Btu/hr for every 12,000 Btu/hr through the evaporator.

APPLICATION ISSUES

Siting and Recirculation

When the saturated air leaving the cooling tower is drawn back into the intake of the tower, the recirculation that occurs degrades the performance of the tower. Wind forces create a low-pressure zone on the downwind (lee) side of the tower that causes this phenomenon. Wind forces on the lee side of the building can also create downward air movement. When cooling towers are located in such a way that the discharge from one tower is directed into the intake of an adjacent tower, recirculation can also occur. Recirculation is a greater problem when cooling towers are confined within pits, or have screen walls surrounding them. If the tower is sited in a pit or well, it is essential that the tower manufacturer be consulted to determine the proper location of the outlet and minimum clearances for the air intake. As previously discussed, the potential for recirculation is greater with forced draft towers than with induced draft towers.

The Cooling Tower Institute (CTI) recommends that recirculation effects be accounted for in the selection of the tower. Their tests show that as much as 8% of the discharge air could be recirculated back into the intake and that the worst conditions occur with winds of 8 to 10 miles per hour. Where recirculation is a concern, a rule of thumb is that the entering wet-bulb (EWB) temperature used to select the tower should be increased by 1°F above the ambient temperature to account for recirculation effects.

Cooling Tower Control

In HVAC applications, chiller evaporator loads vary depending on weather and building occupancy, and the quantity of heat rejected by the condenser varies accordingly. The cooling tower will always reject all the heat from the condenser. However, the temperature of the cold water return to the condenser will decline at lower loads.

Various methods are used to control cooling tower capacity; the common control methods are:

On/Off: Cycling fans is a viable method but at relatively cold temperatures, the fan may cycle on and off too frequently. The maximum number of fan cycles is about 8 per hour.

This may lead to increased wear on belts and drive (if used) and can lead to premature motor failure. This is the least favorable method of controlling temperature. Thus, many cooling towers are equipped with water bypass loops. In most applications, water bypass control is only used at low temperatures when fan cycling could be a problem.

Two-Speed Motors: This method of control adds an intermediate level of cooling between full-on and full-off. This results in considerable fan energy savings, since fan energy varies with the **cube** of flow rate. Thus, fan energy at 50% air flow is only 12% of the fan energy at full air flow.

Caution - One pitfall with two-speed fans is that when switching from high to low speed, the fan rpm must reduce to below low speed before energizing the low-speed step.

Pony Motors: This is another version of the two-speed approach. A second, smaller motor is belted to the fan shaft. For low-speed operation the larger motor is de-energized and the smaller motor energized for a lower speed. This is a cost-effective and energy efficient approach. Again, when going from high speed to low speed, the fan must slow down sufficiently before energizing the low-speed motor.

Variable-Speed Drive (VSD): Adjustable frequency drives can be added to the motors for speed control. This method provides the best temperature control performance and is the most energy-efficient method of control. It may also be the most expensive but studies indicate that the payback period in most cases is less than 18 months. When comparing VSDs with other approaches, the cost of control points for each alternative should be carefully factored into the analysis.

Caution - One pitfall to avoid with VSDs is to not run the fans at the “critical” speeds. These are speeds that form resonance frequency vibrations and can severely damage the fans. Gear drives, where used in cooling towers, will limit minimum fan speed to 50% to provide adequate gear lubrication unless an oil pump is installed. Otherwise minimum fan speeds of 10% are required to provide necessary motor cooling.

Modulating Discharge Dampers: Used exclusively with centrifugal fans, discharge dampers built into the fan scroll can be modulated for capacity control. This is a cost effective way to accomplish close temperature control. Although it does save energy by “riding the fan curve,” other methods of capacity control may provide better energy savings results.

Water Issues

Water use in a cooling tower is tied to two factors: the heat rejection load and the blowdown rate, which is the amount of water that is discharged to prevent the accumulation of solids in the cooling water. The evaporation due to the heat load is approximately 1,050 Btu/lb of water and the blowdown rate can vary depending on makeup water quality, the treatment program, and the tower's construction materials.

Water Treatment

Cooling tower water must be treated to prevent bacterial growth and maintain the concentration of dissolved solids at acceptable levels to prevent scale and corrosion.

Bacterial Growth: The typical method of controlling bacterial growth is to add biocides at prescribed intervals and to keep the cooling tower water circulating. If the tower will not be operated for a sustained period of time, then the cooling water should be drained. Ozone is a very aggressive oxidizer and when properly applied can be effective at reducing biological growth. One pitfall in the use of ozone is that if left unchecked, large concentrations of ozone will cause runaway corrosion of piping and cooling tower basins. Biological control is relatively easy to accomplish and is essential to the safe operation of the tower. ASHRAE has published Guideline12-2000, minimizing the Risk of Legionellosis Associated with Building Water Systems.

Dissolved Solids: Water evaporated from a cooling tower does not contain dissolved solids. Thus, the concentration of dissolved solids will increase over time if only enough water is added to the tower to compensate for evaporation. To maintain the dissolved solids at acceptable levels, most towers periodically discharge some water and replace it with fresh water. This process is called **blow down**. It the level of dissolve solids increases too high, **scale** will be begin to form, and/or the water may become corrosive and damage piping, pumps, cooling tower surfaces and heat exchangers. Usually, the primary dissolved solid to control is calcium carbonate $CaCO_3$. Control of the pH (acid levels) is extremely important. Usually acids, inorganic phosphates or similar compounds are commonly used to control pH.

Corrosion Control: Cooling towers are very good air scrubbers. A 200-ton open cooling tower can remove 600 pounds of particulate matter in 100 hours of operation. Because they are open to the atmosphere, the water is oxygen-saturated which can cause corrosion in the tower and associated piping. Corrosion can be caused by high oxygen content, carbon dioxide (carbonic acid), low pH, or high dissolved solids. Blowdown is the most practical solution.

Blowdown: Towers evaporate water, leaving behind calcium carbonate (hardness) that can precipitate out on the tubes of the condensers and decrease heat transfer and energy efficiency. To control dissolved solids a portion of the flow of the tower should be discharged into the sewer. A rule of thumb is that for a build-up of no more than 2 to 4 concentrations of hardness, the blowdown rate should be about 0.5 to 1.0% of the total flow rate.

Blow down can be accomplished by continuously adding and removing a small quantity of water, periodically draining and refilling the cooling tower reservoir, or by metering the conductivity of water and adding fresh water only when needed. By far the most efficient method is to meter the conductivity of water, which increases in proportion to the level of dissolved solids, and add fresh water only when needed.

The required quantity of blow down water depends on the acceptable quantity of dissolved solids in the tower water, $\text{ppm}_{\text{Target}}$, the quantity of dissolved solids in the makeup water, $\text{ppm}_{\text{Makeup}}$, and the evaporation rate, (ER). The target level of dissolved solids is typically quantified in cycles of concentration (COC), where:

$\text{COC} = \text{ppm}_{\text{Target}} / \text{ppm}_{\text{Makeup}}$

For example, if the quantity of dissolved $CaCO_3$ in the makeup water, PPMmu, is 77 ppm and the maximum level to prevent scaling, PPMtarget, is 231, then the cooling tower water must be maintained at three cycles of concentration:

$\text{COC} = \text{ppm}_{\text{Target}} / \text{ppm}_{\text{Makeup}} = 231 \text{ ppm} / 77 \text{ ppm} = 3$

By applying mass balances, it can be shown that the blow down water (BD) required maintaining a certain number of COC is

$\text{BD} = \text{ER} / (\text{COC} - 1)$

The total makeup water (MU) required, is the sum of the water added for evaporation and blow down:

$\text{MU} = \text{ER} + \text{BD}$

For example for a 1,000 gpm tower with a 0.75% evaporation rate and $CaCO_3$ concentration at 3 Cycles, the quantity of makeup water required would be about:

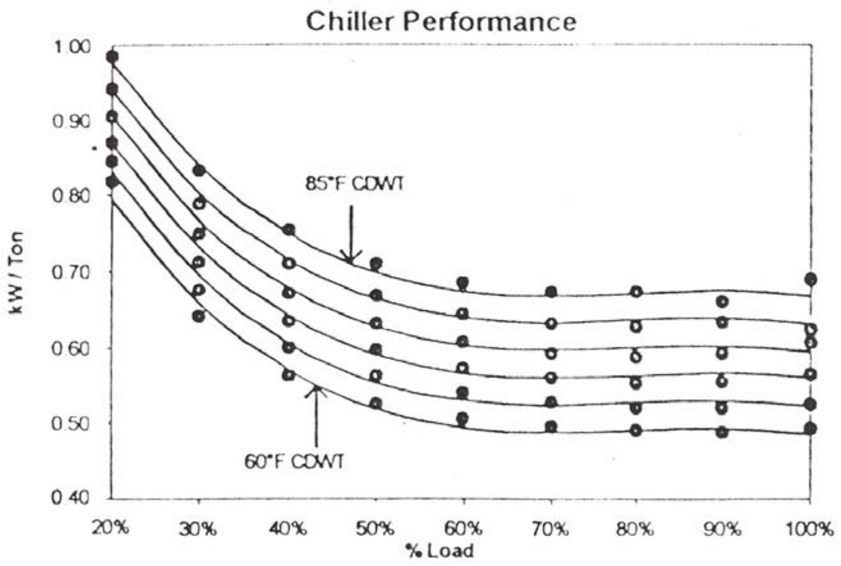
ER = 0.75% x 1,000 gpm = 7.5 gpm

BD = ER / (COC –1) = 7.5 gpm / (3 – 1) = 3.75 gpm

MU = ER + BD = 7.5 gpm + 3.75 gpm = 11.25 gpm

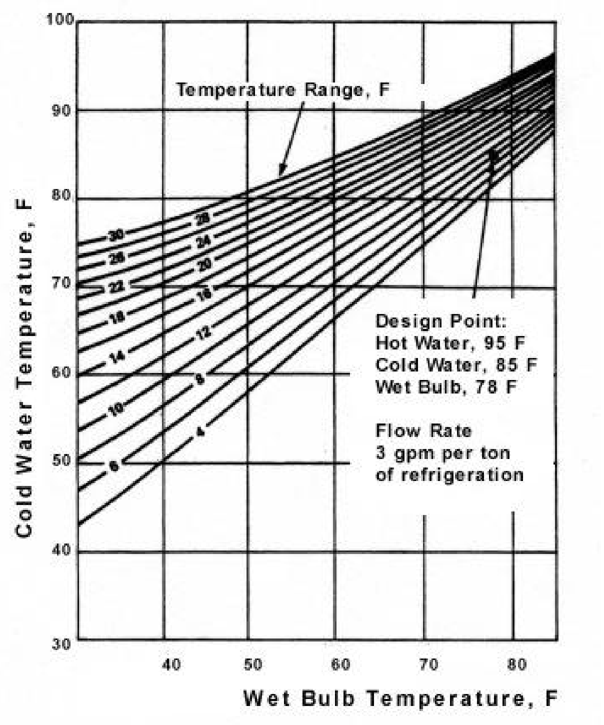
WATER COOLED CHILLER PERFORMANCE

The energy efficiency of water-cooled chillers is typically reported in terms of kW of power to the compressor per ton of cooling generated. Note that kW/ton rating does not include the power to the required cooling tower fan and pump. Typically, cooling tower fan power adds an additional 0.05 kW/ton, and cooling tower pump power adds about 0.04 kW/ton. Performance data from a typical single-speed water-cooled chiller are shown below. The data show that chiller energy efficiency decreases at part-loads and high condenser water temperatures from the cooling tower.



Performance of Cooling Towers

Given a fan selection, flow rate, range, entering wet bulb, and fill volume, cooling towers have a wide range of performance characteristics. Typical performance curves show the relationship between these variables at different operating conditions. In reviewing the typical performance curve, one feature not well understood is that for a given range, as the entering wet bulb (EWB) decreases, the approach increases. As EWB drops, it is likely that the load (range) will also decrease for the same flow rate.



Notes:

- The range is determined by the cooling tower heat load imposed by process and water flow rate and NOT by the size or capability of the cooling tower. Increasing the range reduces the water flow rate and the pumping power.
- Striving for a low approach temperature is desirable, as it lowers the condenser temperature. A small approach means a larger cooling tower. Approach temperatures are usually 5 to 7°F or greater to design wet bulb temperature. For much of the continental United States, a typical design wet bulb temperature is 78°F.

Cooling towers are relatively inexpensive when compared to the total cost of a chiller plant, and incremental increases in tower size and energy efficiency can be purchased at a very low cost. Every effort should be made to optimize the selection of the tower. Matching larger fill volumes with lower fan capacities is a very good investment. For a given design of a cooling tower the manufacturer will normally attribute a maximum and minimum flow condition to the tower. The maximum flow is usually based on the capacity of the water distribution system within the tower to adequately distribute the water over the fill. Too much flow will overflow the tower distribution pans and create a situation where the tower does not get adequate mixing of air and water to perform properly. At minimum flow the water may not distribute evenly across the entire fill. This creates voids where there is no water in the fill. When this happens the air stream will tend to travel through the fill area with no water and will not mix properly with the fill area that has the water. This creates a significant decrease in the expected performance of the tower. Another drawback to operating under the minimum flow is that at the boundary where the water and high velocity air meet, a condition is created where the water is carried up through the fans and the tower “spits” water. Prolonged operation below the minimum water flow can also cause scaling to occur on the fill where the water is missing.

ASHRAE Standard 90.1-2004 establishes energy performance requirements for heat rejection devices. Currently, it requires >38.2 gpm/hp for axial fan towers and >20.0 gpm/hp for centrifugal fan towers at the design conditions of 95°F condenser water return, 85°F condenser water supply and 75°F outdoor air wet-bulb temperatures.

In general, propeller fan cooling towers use ½ of the energy of centrifugal fan towers for the same duty and have a lower first cost. Exceptions are provided for installations with external static pressure such as ducted inlet or discharge or the need for sound traps. If an acoustical criterion is important the reader is encouraged to investigate low-noise draw through towers with propeller fans. These towers have the following features:

- Heavier gauge of metal on the fans
- Slower fan speeds
- Low pressure sound traps

Performance Certification

Independent certification of thermal performance is increasingly required, with most manufacturers participating in the Cooling Technology Institute (CTI) certification program under CTI STD 201 (note that the CTI performance test code is CTI STD 105 for open cooling towers and CTI 105S for closed circuit cooling towers). The California Energy Code, known as Title 24, mandates the use of CTI certified open cooling towers in its 2005 edition (note that no requirements exist for field erected towers, which are not often used in HVAC applications). This same requirement is being considered for the 2004 edition of the ANSI / ASHRAE / IESNA Standard 90.1, Energy Standard for Buildings except Low-Rise Residential Buildings, adopted by many building codes in the United States.

As most other components of the system are certified, specifying CTI certification on cooling towers reduces the likelihood, as well as the resultant liability, for deficient towers on a project for the consulting engineer, contractor, and the owner, while also eliminating the need for costly field performance tests.

Certification is important because temperature matters, since even small deviations from the expected design have a substantial impact on the system over time. For instance, a cooling tower that is 20% deficient elevates the leaving water temperature by approximately 2.5°F (1.4°C). Typically, this higher water temperature will result in 6% more energy being consumed by the chiller. On a 500-ton system during peak conditions, this 6% penalty translates into approximately 17 kW of additional energy usage, resulting in higher electricity bills for the owner. Furthermore, the cooling tower has to work harder, at all times, not just at peak conditions, to meet the load, adding to the overall energy penalty. A tower that is 20% deficient can cost an owner from three to eight times the original purchase cost of the cooling tower over its operating lifetime in terms of higher total energy costs.

Benefits

The advantages of evaporative cooling stem from several key factors.

- First, cooling towers use the ambient wet-bulb temperature of the entering air as the heat sink, which is typically 10°F to 30°F (5.5°C to 16.7°C) lower than the dry bulb, depending on the local climate. The lower the temperature of the heat sink, the more efficient the process.
- Second, the evaporative cooling process involves both latent and sensible heat transfer (primarily latent) where a small portion of the recirculating flow is evaporated to cool the remaining water. For every pound of water evaporated into the airstream, approximately 1,050 Btu of heat is rejected.* In contrast, a pound of air at standard conditions has a heat content of only 0.24 Btu/1b-°F, meaning that much greater air volume is required to reject the same heat load in air cooled (sensible only) cooling systems as compared to evaporative cooled systems. For instance, a typical open cooling tower requires 250 cfm per ton of heat rejected while air-cooled condensers, operating at a higher condensing temperature, require 600 to as much as 900 cfm per ton with correspondingly higher fan horsepower (kW). * Every pound of water evaporated into the

airstream allows the air to carry away approximately 1,050 Btu (1 108 kJ) of energy from the process to be cooled. This value varies slightly with climate.

- Third, due to water's ability to efficiently transport large quantities of heat over relatively long distances, water-cooled systems allow the economical separation of the compression and heat rejection equipment. For example, the chiller can be located in a basement machine room and the cooling tower on the roof, many floors above. This typically is not an option with air-cooled systems. Multiple air-cooled systems on the roof, with their duct penetrations, also increase the chance of compromising the roofing system.

These reasons combine to explain why evaporative cooling towers are smaller and require much less fan energy than air-cooled equipment.

Limitations

- There are some limitations to using cooling towers. Their ability to cool is based on how much water is lost due to evaporation. The evaporation from a cooling tower is based on the quality of air in the surrounding area. If an area has high humidity, less water will evaporate than in a dry climate.
- Limitations are really restricted to location and that relates to potential contamination of air intakes by Legionella bacteria that might be present in the cooling tower basin;
- Water treatment and corrosion are of greater concern in the open-circuit cooling tower. Chemical or non-chemical water treatment techniques incur continuous expenditure.

PART- 4 CLOSED CIRCUIT FLUID COOLERS

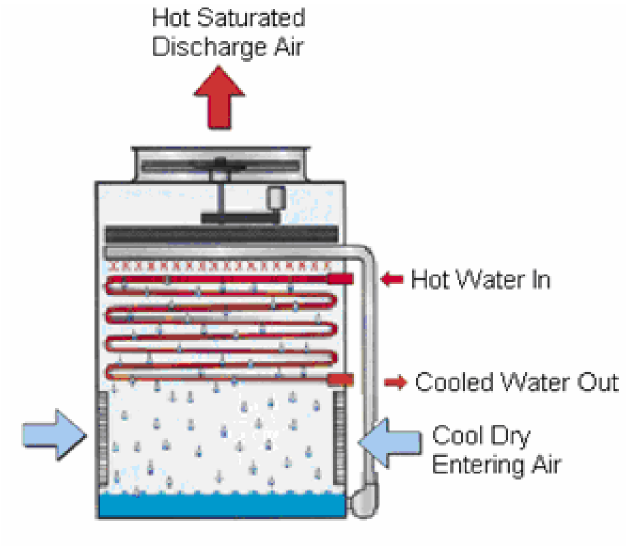
Closed circuit towers, also known as a “fluid cooler,” are the hybrids that pass the condenser water through a tube bundle, upon which water is sprayed and a fan-induced draft applied. The resulting heat transfer performance is much closer to that of a wet cooling tower, with the advantage provided by a dry cooler of protecting the working fluid from environmental exposure. It combines a heat exchanger and a cooling tower into one relatively compact design.

Principle of Operation

The condenser water (CW) flows through a finned tube coil of the closed loop and water is sprayed over the coil. Simultaneously, air is drawn in through the air inlet louvers at the base of the cooler and travels upward over the coil opposite the water flow. A small portion of the water is evaporated which removes the heat. The warm moist air is drawn to the top of the closed circuit cooler by the fan and is discharged to the atmosphere. The remaining water falls to the sump at the bottom of the cooler where it is recirculated by the pump up through the water distribution system and back down over the coils.

The heat transfer process from CW to the spray water is purely sensible as the result is a reduction of say 5.5°K in the CW temperature. The increase in the spay water temperature is transferred to the cooling air in an evaporative process.

A closed circuit cooler does not impact upon sub-cooling or superheat of the refrigeration process. Sub-cooling happens in the condenser vessel in whatever form it may be.



CLOSED CIRCUIT COOLER

Benefits

The primary advantage of a closed circuit fluid cooler is that the fluid (condenser water) is located within a closed loop of coil (rows of tubes) rather than being open to the environment. The closed piping can be advantageous if the fluid:

- Has a high pressure (for instance if the tower is located below the condenser);
- Is mixed with fluids from other systems (like the chilled water); or
- Has the primary pump located remotely from the tower.

With proper initial chemical treatment, the fluid does not foul the condenser tubes, so chiller maintenance is reduced and energy efficiency is always at peak.

These advances have improved the functionality of closed circuit towers as well as lowered the point where they can be economically justified over open towers in many applications. For instance, by closing the condenser water loop, condenser tube bundle cleaning can be nearly eliminated while the chiller operates at peak performance at all times. If any fouling and scaling occurs, it does so on the open side of the tower, where it can be easily controlled through a proper water treatment program. The chiller energy savings and reduced maintenance expenses often can offset the higher cost of the closed circuit tower.

Closed circuit towers can offer a hydraulic advantage on certain projects. Open towers must be installed above the heat source, while closed circuit towers can be located below since the process fluid is contained in a closed loop and the spray water re-circulates within the tower itself. This flexibility can help solve site location problems for architects and engineers.

Limitations

- Because of the additional heat exchange process, for the same capacity as an open tower, the closed circuit fluid cooler is physically much larger and significantly more expensive than conventional open towers.
- Closed circuit coolers are usually very heavy due to amount of metal in their construction, and the footprint can be relatively small. Slab or frame strength for the support structure must be checked;

- They are difficult to clean. By the very nature of the evaporative effect, scale will build up on the outside of the coil bank making it almost impossible to clean;
- Ambient wet bulb is a selection limitation as the heat transfer depends upon the approach between spray water temperature and the ambient wet bulb temperature. The higher the approach, the higher will be the cooling effect;
- While approach is a key factor, selection criteria is ambient wet bulb and CW flow.

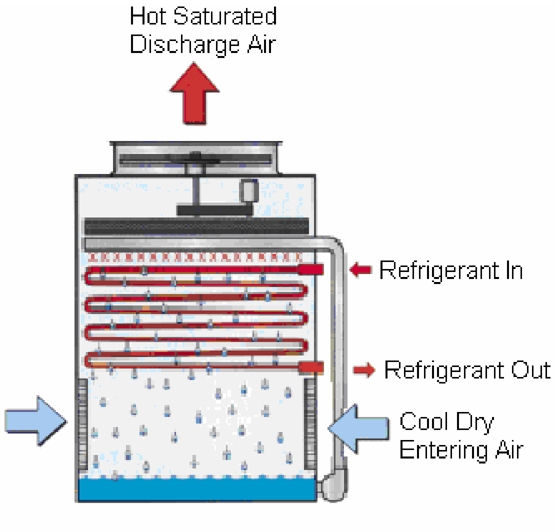
PART -5 EVAPORATIVE CONDENSERS

An evaporative condenser is similar to closed circuit cooler but refrigerant replaces the water in the tubes. Refrigerant passes through a copper tube bundle in the evaporative cell and water cascades over its outer surface. Air is blown (drawn) across the coil and some of the water evaporates causing heat transfer. The hot gas from the compressor condenses inside the tubes. This results in the efficient cooling of the refrigerant.

There is a sump in the bottom of the condenser to store water and a pump draws the water to spray on the outside of a coil. In the winter, the pump is de-energized and only the air flowing across the coils is sufficient to cool the refrigerant. The chiller thus becomes air-cooled.

The design of system pipe work around an evaporative condenser should not be undertaken unless the designer has a clear understanding of refrigeration. The same rules apply to an evaporative condenser as to an air cooled condenser.

- A receiver is essential regardless of what some contractors will try to impose upon the design;
- A separate sub-cooling coil is also essential for the proper control of liquid flow;
- The condensate line out of the condenser coil must drain freely to the top of the receiver of the condenser simply will not work and there will be high head pressure problems;
- Flash gas must be vented off the top of the receiver to hot gas line before it enters the condenser, and under no circumstances should two condensers be used in a common circuit unless the design and installation is carried out by experienced people. The balance of liquid flow out of condensers must be precise or one of the condensers will not work.



EVAPORATIVE CONDENSER

Evaporative condensers are a cross between a cooling tower and an air-cooled refrigerant condenser. These devices are primarily used in the industrial refrigeration business and have little application in the HVAC industry. Some manufacturers produce small packaged water chillers with evaporative condensers as an integral component.

The effectiveness of the evaporation of the water and the refrigerant in the heat transfer process means that for a given load, evaporative condensers can have the smallest footprint of any heat rejection method. The evaporative condenser causes lower condensing temperatures and, as a result, is far more efficient than air-cooled condensing. Maintenance and control of evaporative condensers is similar to the closed circuit fluid cooler. Like cooling towers, the style of the tower can significantly impact fan energy power.

Limitations

- Limitations for the use of an evaporative condenser are the same as for an air cooled condenser except the foot print. The physical size of an evaporative condenser is less than needed for an air cooled solution;
- The greatest limitation is capacity. As a rule of thumb a field piped refrigeration system will have a gas charge of up to 4.5lbs/TR and that means a 300TR plant will 1350 lbs of chemical refrigerant in circulation. The potential for a leak is high, and the impact of the leak is financially significant but an ecological disaster. It is suggested that 200TR be the maximum size of plant to use an evaporative condenser;

- Ambient wet bulb is critical and it again relates to approach. Higher wet bulb ambient conditions produce less heat rejection capacity. It is suggested that wet bulb selection criteria be 0.5°K above the normal design ambient.

PART- 6 ADIABATIC CONDENSERS

Adiabatic condensers are in essence an air cooled condenser but with the ambient air pre-cooled by wetted pads. Ambient air is drawn through the pads to be adiabatically cooled to about 80% to 85% saturation before entering to condenser coil.

Water is re-circulated over the pads when needed i.e. if ambient conditions are low enough, the water is not used and the condenser is a straight air cooled device. To control water use the spray is energised at ambient temperatures over 70°F and pulsed on / off dependent on this temperature. Figure below shows a typical adiabatic condenser.

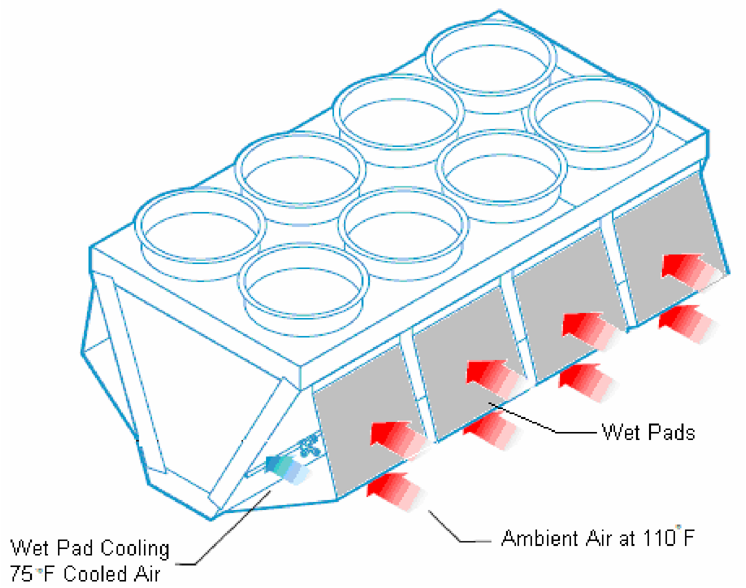


Figure: Adiabatic Condensers

The adiabatic cooling technology relies on the difference between the ambient air dry bulb temperature and the wet bulb temperature. During the summer months, this differential is high. The wet bulb temperature is lower in the summer, as the amount of moisture in the air is less. This allows more cooling of the air, as it can absorb more moisture. The more moisture it can absorb, the more heat is removed from the air and hence a lower air temperature results. In short, in warmer periods, the potential savings are the greatest. All refrigeration effects and impacts are the same as for an air cooled solution with the exception that water cooled performance can be achieved from an air cooled solution. The installation still requires a receiver, but there is no sub-cooling coil provided. Sub-cooling is achieved within the condenser coil in similar manner to a shell and tube condenser. In essence, the condenser coil is larger than it need be to condense the hot gas to liquid. However, this fact makes the receiver an imperative.

Limitations

- The largest adiabatic cooler will reject 250 TR. This equates to the cooling effects to roughly 200 TR (assuming 25% heat of compression). The foot print for a horizontal unit is 7.5m x 2.12m with an access need of 1.2m all around;
- Noise is often a significant problem due the amount of air needed to dissipate the heat. The largest unit available has ten fans and the noise level can exceed 81dBA;
- Fin material for the coils is susceptible to corrosion so that is also a factor in their selection. However, the pre-cooling pads act as a filter and washer to protect the coils. The impact of corrosion is not usually as high as for an air cooled condenser;
- Water is needed but the consumption is minimal;
- Capital cost is higher than water cooled or air cooled solution. However, if the plant size is large enough to need two air cooled condensers, the adiabatic solution is more economical.

Advantages

If there is sufficient real estate available for an air cooled solution and the plant size is less than 200 TR, an adiabatic condenser will provide the best energy result of all heat rejection methods.

Water cooled performance is achieved without the need for water treatment.

PART- 7 SELECTING THE RIGHT SYSTEM

Selection of heat rejection equipment has traditionally been a choice between higher energy consumption of an air cooled solution v/s high water consumption of a water cooled solution. There is a fine line that needs to be examined on a case by case basis. The salient parameters are:

1. **The Capacity of Plant:** The air-cooled machines are easy to install and takes lower space compared to water-cooled machines on lower sizes. The space requirements for air-cooled machines however increase significantly for nominal capacities above 200 TR. If the plant is larger than 200 TR and is not packaged, it should be water cooled as:

    - It will provide the best energy result;
    - The capital cost will be appropriate to the size of plant;
    - Chemical refrigerant will be minimized.

    Multiple air cooled DX systems are possible after analyzing all pros and cons.

2. **Availability of Water:** The places where water is scarce, every drop of water must be carefully used in an economically feasible manner. The water demand in some regions is primarily met by groundwater abstraction, desalination plants and recycled wastewater. All water treatment is costly. As an estimate desalinated water production costs range from $ 2.5 per 1000 gallons to $ 4.4 per1000 gallons with an average cost of $ 3.0 per 1000 gallons. Air cooled condensing is preferred where water is scarce and/or involve very high treatment costs.

3. **Quality of Water:** The quality of water does matter. Ozone treatment or automatic biocide dosage shall be required to limit the growth of Legionella bacteria associated with water cooled options.

4. **Space Requirements:** Water cooled condensers are much more compact and require no remote outdoor mounting and piping, rooftop structural preparation or outdoor NEMA-4 electrical service. Where equipment room floor space is at a premium, self contained air cooled chillers, or remote split systems are preferred.

5. **First Costs:** A water-cooled chiller will have a higher first cost than an air-cooled chiller. The additional maintenance costs associated with open cooling towers like water treatment to control bacterial and fungal growth as well as water softening to

remove particulate and prevent scaling in the system should also be considered. Unlike water cooled options, air cooled condensers do not require pumps, auxiliaries and associated piping. With lesser components the associated civil costs also tend to be low

6. **Operating Costs:** The kW/ton energy consumption of air-cooled systems is higher compared to water-cooled machines and for unit capacities exceeding 200TR, water cooled machines consume less energy. Air cooled condenser requires some potential temperature difference in order to reject heat, so the refrigeration system must operate at a higher head pressure and temperature to produce this temperature difference. Air cooled condensers normally requires between 125°F to 130°F condensing temperature to reject heat to a 100°F ambient, while a water cooled condenser can operate at 105°F condensing temperature and reject its heat to a 95°F water stream. Because air is a poor conductor of heat, water cooled condensers can operate with a much lower approach temperature. However, the operation cost of an air-cooled condenser system on small capacities shall be more economical because of the lower number of power driven auxiliaries and the zero water treatment costs.

7. **Maintenance:** Water-cooled systems will always cost more to maintain due to the constant water treatment requirements and the need for regular tube cleaning. Water-cooled chillers will generally last longer, however, particularly in harsh environments such as near oceans where salt in the air can significantly shorten the life of air-cooled condensers.

8. **Potential for Heat Recovery:** Heat recovery is easier to obtain and control when using water cooled condenser because water has a far greater heat capacity than air. Heated water from the refrigeration cycle can be diverted to heat other processes and even provide space heating during winter months.

9. **Flexibility of Control:** Water-cooled machines provide better control of indoor conditions at extreme ambient conditions. The performance of an air-cooled condenser machine reduces significantly at higher ambient temperatures and requires considerable over sizing to overcome the extreme high ambient temperatures. The thermal efficiency of air-cooled condensers is lower than that of cooling towers.

10. **Other Governing Criteria:** Air-cooled condensers are restricted by distance separation and the installation height differential between the evaporator and the condensers. Typically the condensers should not be more than ~120 ft above or below and not more than ~ 240 feet away from the chilling machine.

Energy Efficiency

The efficiency of a chiller is a measure of the cooling capacity versus the required input power into the chiller. The table below shows typical efficiencies for both water-cooled and air-cooled chillers:

Chiller Efficiencies

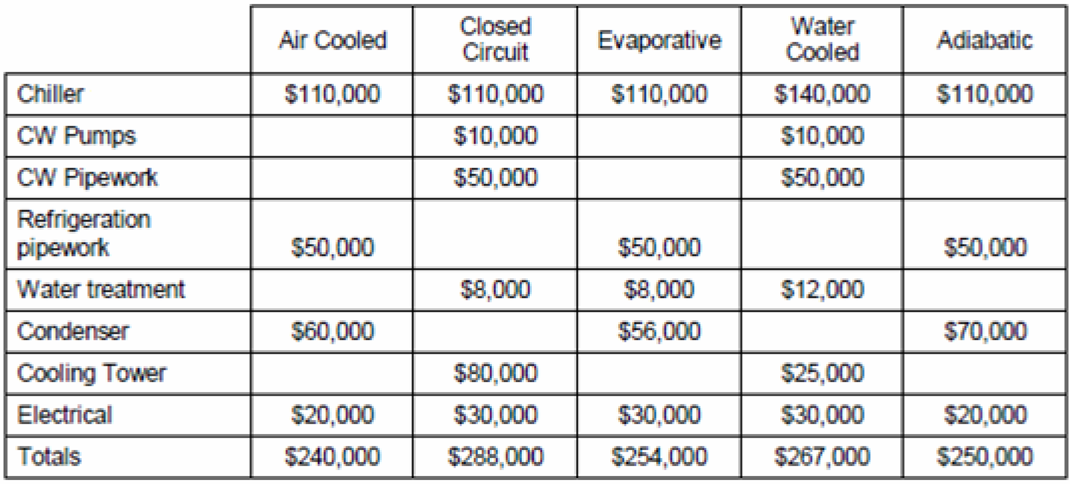
Air-cooled (including condenser power >150 tons)	EER	COP	kW/ton
ASHRAE Standard 90.1 1999	9.6	2.8	1.26
Good	9.9	2.9	1.21
Best	10.6	3.1	1.13

Water-cooled (>300 ton centrifugal compressor)	EER	COP	KW/ton
ASHRAE Code 90.1 1999	16.7	4.9	0.72
Good	18.5	5.4	0.65
Best	26.7	7.8	0.45

Most air-cooled system efficiencies are specified using a measure called the Energy Efficiency Ratio (EER), which is the Btu per hour of cooling capacity per watt of input power. Water-cooled chiller efficiencies are often specified in terms of kW of input power per ton of cooling. One ton of cooling capacity is equal to 12,000 Btu/hr which is the cooling capacity made available by melting one ton of ice in an hour. At first glance a water-cooled chiller appears to be a far more efficient solution, but one must factor in the additional energy associated with cooling tower fans and pumps.

ECONOMIC ANALYSIS

The following matrix details indicative capital costs for each method based upon a 200 TR chilled water plant:

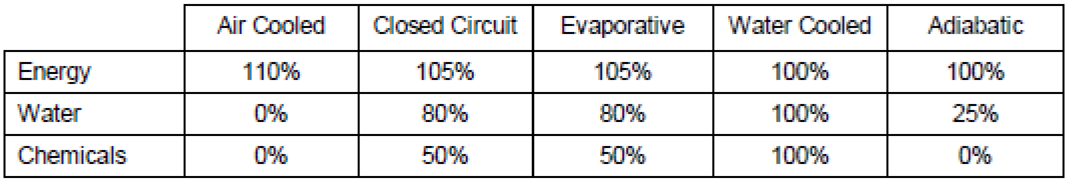


	Air Cooled	Closed Circuit	Evaporative	Water Cooled	Adiabatic
Chiller	$110,000	$110,000	$110,000	$140,000	$110,000
CW Pumps		$10,000		$10,000	
CW Pipework		$50,000		$50,000	
Refrigeration pipework	$50,000		$50,000		$50,000
Water treatment		$8,000	$8,000	$12,000	
Condenser	$60,000		$56,000		$70,000
Cooling Tower		$80,000		$25,000	
Electrical	$20,000	$30,000	$30,000	$30,000	$20,000
Totals	$240,000	$288,000	$254,000	$267,000	$250,000

Obviously there is little difference between the options with air cooled as the less cost and closed circuit cooler as the highest. The selection is then based upon other impacts such as energy, water and real estate.

Environmental

Main environmental impacts are energy and water consumption. The following matrix indicates potential environmental impact:



	Air Cooled	Closed Circuit	Evaporative	Water Cooled	Adiabatic
Energy	110%	105%	105%	100%	100%
Water	0%	80%	80%	100%	25%
Chemicals	0%	50%	50%	100%	0%

Note - the above analysis is indicative and the actual consumption need to be assessed for each site.

Evaporative water-cooled systems, whether open or closed-circuit, are the best overall heat rejection solution for most installations. These systems offer design flexibility, save energy, and conserve resources while protecting and respecting the environment.

Summary

Water cooled condensers are typically specified when a supply of cooling water is readily available. Due to the cost of city water, water treatment, pumping costs and maintenance of a water delivery system, air cooled condensing is preferred in applications where service water is not required for other plant operations or where existing heat rejection capacity is insufficient. In general the following rules apply:

- For cooling loads below 100–125 tons, the initial capital and recurring maintenance costs for a water-cooled system are rarely justified and the **chiller(s) shall be air-cooled**.
- Above 200 tons capacity systems and with the use of rotary compressor chillers, the water-cooled condensing option becomes justifiable. Note that the **centrifugal chillers** are always water cooled due to lower compression ratio.
- Between 100 and 200 tons peak cooling load, it becomes a matter of the owner's ability to deal with the maintenance requirements of a cooling tower system and the capital funds available.