Chapter 6

Alternatives to Wet Cooling Towers

The previous chapter was devoted to understanding and taking control of the cooling system. This chapter will discuss strategies to minimise the cooling load in air-conditioning and refrigeration systems, which is the main requirement for cooling water in these systems. By improving energy efficiency of air-conditioning and refrigeration systems both energy and water savings can be realised. It will discuss alternatives to wet cooling systems; in particular, air-cooled chillers/condensers, hybrid cooling systems, combination of air-cooled and wet cooling systems and geothermal applications. Their suitability will depend on individual circumstances such as adequate land area.

6.1 Air-conditioning and Refrigeration Systems

Before a discussion on energy saving options can begin, a basic understanding of air-conditioning system is required. A refrigeration system has many of the components of an air-conditioning system. Air-conditioning and refrigeration can be achieved by mechanical and absorption refrigeration systems. Absorption refrigeration systems are economical when there is a source of cheap energy such as waste heat. However, most facilities do not have access to this and therefore absorption systems are not discussed in this chapter. Chillers are classified as reciprocating, screw and centrifugal depending on the type of compressor used. Reciprocating chiller compressors are used below 700 kWR (200 tons) and screw compressors are used in the range from 140 to 2800 kWR (40 to 800 tons). Centrifugal compressors are available from 263 kWR (75 tons), but are typically used in large installations and can exceed 17 585 kWR (5000 tons) or more. The centrifugal compressor is ideal for air-conditioning systems since it can operate at variable loads, has few moving parts and is economical to run. Figure 6.1 shows a schematic of a typical air-conditioning system and Figure 6.2 shows a photograph of centrifugal compressor and chiller.

The air-handling units circulate a mixture of fresh and recycled air. They transfer the heat contained in a building from air to the chilled water and

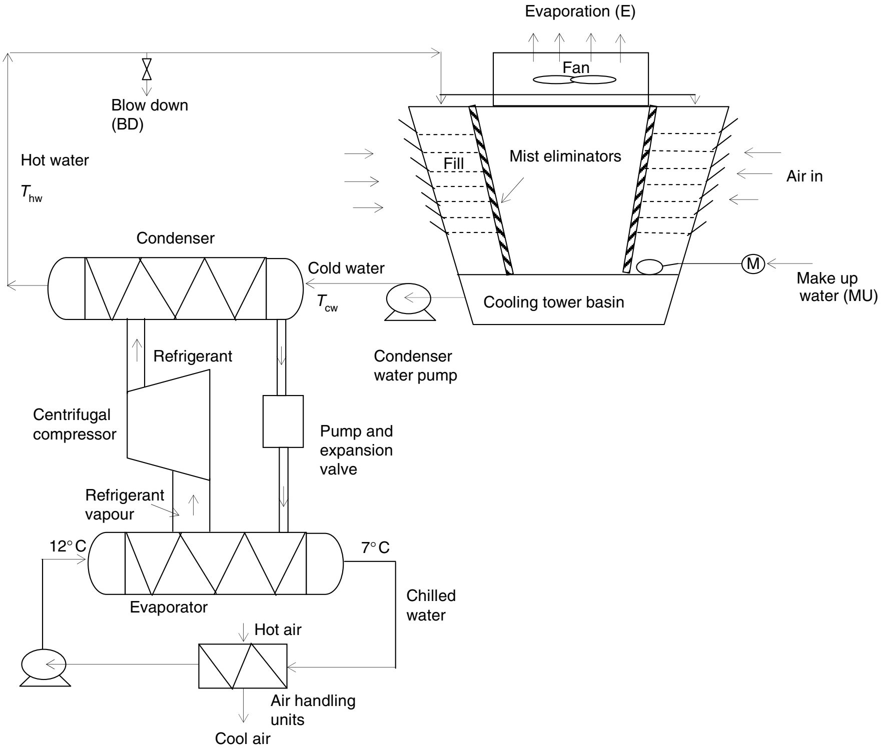

Figure 6.1 A schematic of an air-conditioning system

in the process increasing the chilled water temperatures from 7° C to 12° C (45° F to 54° F). The chilled water enters the evaporator (a shell and tube heat exchanger) where the 'hot' chilled water transfers the heat to the liquid refrigerant. The refrigerant evaporates and in the process creates the cooling effect for the chilled water. The vapour enters the compressor where it is compressed and in the process picks up heat. The high-pressure superheated vapour flows into the condenser (a shell and tube exchanger) where it gives up the heat to the circulating cooling water and in the process is condensed into a saturated liquid. The condenser water temperatures rise from 28° C–32° C (80° F–90° F) to 32° C–38° C (90° F–100° F). The condenser water dissipates the heat in the cooling tower. The liquid refrigerant is further sub-cooled in the expansion device and flows backs into the chiller for the cycle to repeat again.

6.2 Energy Conservation = Water Conservation

Process cooling and air-conditioning can account for a significant portion of the organisation's electricity bill. For instance, in a brewery approximately 32% of electricity is consumed in the refrigeration system. It is the second largest energy user after pumps and compressors. Therefore by reducing

Figure 6.2 A photo of a centrifugal compressor and chiller

energy consumption, the bottom line improves, reduces water usage and reduces greenhouse gas emissions.

Ways to minimise energy consumption in air-conditioning and refrigeration systems are summarised in the following rules.

Rule 1: Operate the system only when needed

In comfort cooling applications, air-conditioning systems including compressors and cooling towers should be operated only when areas are occupied. Many buildings are unoccupied during weekends and after 5PM, yet the air-conditioning systems are kept operating in buildings that lack a comprehensive building management system. In process applications use the refrigeration system only on a need-to-use basis. Eliminate non-essential heat loads.

Improved temperature control of process temperatures, cooling water temperatures and cooling water flow rate lead to optimal operation and efficiency.

In batch-operating plants it is important to shut off cooling water to process equipment once the cooling needs are met. A common occurrence in plants with manual control of cooling water flows is that the cooling water pumps operate long after the process has finished. With automatic temperature control this is easily avoided.

Rule 2: Eliminate over-cooling

Over-cooling can be eliminated by revising operating procedures and modifying air-conditioning system controls. Rather than maintaining a constant temperature, allow the temperature to fluctuate within a dead ban range.

Rule 3: Carryout timely maintenance

It is often possible to gain energy efficiency improvements at a very low cost by carrying out timely maintenance of the refrigeration and ancillary equipment. Simple things such as shutting doors and cleaning of condenser and evaporator units and timely removal of scale improve heat transfer. It is estimated that 3 mm of scale will increase power input by 30% and reduce power output by 20%.

Rule 4: Reduce lighting load

Lighting in a typical office building accounts for 40% of the energy demand. Whilst in industrial plants lighting accounts for about of 5–7% of the energy demand, it is still a sensible measure to reduce energy usage where practical.

Less lighting = less heat generated = less air-conditioning load

In office buildings it is claimed that savings of 30% are achievable without impacting on use or comfort. The improvement measures can take the form of switching off lighting when not required or installing movement sensors to switch on lighting, replacing energy-hungry lighting with more efficient types such as fluorescent Triphosphor T5 (23% more efficient than a triphosphor T8 lamp [1]) and designing new buildings to have more natural light by having double-height windows and curved ceilings. As a guide, lighting levels in office buildings above 11 W/m^2 is considered to be energy inefficient [1].

Case Study: Louis Stokes Laboratories, National Institute of Health

The Louis Stokes Laboratories of the US National Institutes of Health applied a combination of strategies to improve the efficiency of lighting systems. First, all fluorescent light fixtures were replaced with more efficient T-8 lights and electronic ballasts. Secondly, motion sensor-activated lights and light emitting diode (LED) exit sign were installed. Thirdly, a programmable lighting control system was installed. Lastly, double-height windows and curved ceilings were employed to allow more daylight into the lab space. Based on these measures, the average energy consumption rate per unit of lighting area was reduced to an impressive 17 W/m^2 (1.6 $W/gross\ ft^2$) [2].

Rule 5: Increase building reflection

Designing the building to reduce heat from solar radiation reduces the air-conditioning load especially in sunny hot climates. Experiments in California and Florida have demonstrated that coating roofs with a reflective coating reduces summertime average daily air-conditioning electricity use from 2% to 63% [3]. Two medical offices in Northern California reduced air-conditioning loads by 8 and 12% respectively. For colder climates the energy savings may not be that dramatic since in winter these savings can be negated by the added heating requirements.

Roof gardens provide both cooling and heating benefits. In Germany roof gardens on top of office buildings is quite popular.

Rule 6: Improve building insulation

Building insulation reduces both cooling and heating loads in buildings. Refer to the State or National standards.

Rule 7: Install energy efficient chillers and refrigeration systems

Install energy efficient chillers and refrigeration systems. Modern centrifugal chillers use half the energy usage of models that were installed a decade ago. Potential saving: 1.2% of a facility's total energy use with an average payback of 23 months [4].

Rule 8: Size chillers to better balance the load

Sometimes one large and another small chiller may be more efficient than one large chiller because at part load operation it is less efficient. The cost savings can be significant.

Rule 9: Use the free cooling mode – economiser cycle

Many air-conditioning systems operate with a fixed amount of outdoor air. The mechanical refrigeration load can be reduced by modifying the system to use natural ventilation using cooler ambient air at up to 100% of its supply airflow, when the ambient air is cooler than the return air. This is known as the "economy air cycle". Dampers are opened according to the outdoor dry bulb temperature or by sensing the enthalpy difference between the outdoor and the indoor enthalpy of air. Not operating the air-conditioning system results in energy and water savings. The overall economics, frequency of operation and control logic required needs to be evaluated before going ahead with this option. Energy savings as much as 40% depending on location and load profile can be realised [4].

On the other hand reducing cool room exhaust air flows during summer reduces energy consumption.

Rule 10: Operate at the lowest condensing water temperature

A common strategy to reduce energy usage is to reduce the condensing water temperature. Cooling towers are designed for summer month operation, and therefore during part load operation and in winter months it is possible to reduce the condensing water temperature thus reducing the condenser refrigerant pressure. For example, Table 6.1 shows that a reduction in condenser water temperature from 29.4° C to 21.1° C (85° F–70° F) reduces chiller energy consumption from 0.162 to 0.128 kW/kWR (0.57–0.45 kW/ton), a reduction of 21% [4].

Rule 11: Operate at the highest chilled water temperature

By increasing chilled water temperature by one degree, chiller energy usage can be reduced by 0.6–2.5% [4]. Whilst it increases the power input to the compressor, the gain in refrigeration output is much greater. The efficiency gains are more dramatic at the lower set point temperatures than at higher temperatures. In process applications this may not always be possible. However, the opportunity to do this arises when chilled water flows are throttled indicating that the temperatures are lower than required.

Rule 12: Install variable drive speed fans to the cooling tower

Cooling towers are sized so that they have sufficient heat rejection capacity during summer when the hottest ambient temperatures are expected. When the actual wet bulb temperature is below the design wet bulb temperature or where the heat load appears to be lower, the designed amount of cooling can be obtained with lower airflow rates. As the airflow rate decreases, the fan speed and the motor power requirements also decrease. A variable speed drive fan controlled by the cooling water inlet temperature can decrease both water and energy costs. It is estimated that a saving 30–60% decrease in cooling energy use can be realised depending on load profile [5, 6]. Processes with variable cooling loads such as in batch production systems and those with spare machine capacity are likely to make major savings.

Table 6.1 **Effect of condenser water temperatures on chiller energy usage**

Cooling water temperature		Typical chiller energy consumption		Energy savings
°C	°F	kW/kWR	kW/ton	
29.4	85	0.162	0.57	Base (%)
28.3	83	0.154	0.542	5
26.7	80	0.149	0.524	8
23.9	75	0.138	0.484	15
21.1	70	0.128	0.45	21

Case Study: Chemical Manufacturer UK

A manufacturer of synthetic drugs operates a batch production system which leads to varying cooling loads. After examining its energy usage the company installed a frequency inverter variable speed drive to match fan speed to actual cooling load which resulted in a 60% reduction in electricity consumption.

Adapted from: *Energy Efficiency Best Practice Programme. Case Study 270. Variable Speed drive on a cooling tower induced draught fan.*

Rule 13: Recover waste heat

Another effective way to reduce heat rejection, and hence water consumption, is by recovering and re-using the heat that would otherwise be rejected to the environment. Many water-cooled chillers can be purchased with a heat recovery unit, and depending on the type of refrigerant, the condensing pressure, the design and the application, a significant portion of the waste heat can be recovered. For every kW of heat recovered in a water-cooled plant, up to 1.7 L of water can be saved per hour of operation. Such recovered waste heat can be used in many different ways, such as

- Low grade heat at 30° C–40° C (86° F–104° F) for space heating, reheat of air in air-handling units and as boiled feed water.
- High grade heat – hot water 50° C–70° C (122° F–158° F) as hot water for wash down.

6.3 Alternative Heat Rejection Systems

There are number of alternative heat rejection systems, other than evaporative condensers and cooling towers. Fluid coolers, chillers and condensers can be supplied in air-cooled or in various hybrid cooling designs to reject heat to the environment with minimal water usage. Another option is to use a combination of evaporative and air-cooled equipment. Where there is an excess of low-grade waste heat, absorption chillers can be used either as a stand-alone unit or in combination with electric chillers. The strategy is to use the absorption chillers preferentially during high electric rates.

Then there are alternatives that avoid direct rejection to the environment, such as geothermal systems. The best time to consider these alternatives is when designing a new system or upgrading/replacing an existing cooling system. These technologies are described briefly.

Figure 6.3 A bank of air-cooled condensers

Courtesy of Minus 40 Pty Ltd.

6.3.1 Air-Cooled Condensers

In air-cooled condensers, the refrigerant condenses inside finned tube over which a stream of air flows. The cooling tubes/coils have fins to increase heat transfer. The air is blown by fans and cooling takes place due to conduction and convection. Figure 6.3 shows a bank of air-cooled condensers.

The advantages of air-cooled chillers and condensers are well known. They do not require cooling water and therefore the associated maintenance issues of corrosion/scaling, risk of *Legionella* and chemical treatment costs are eliminated.

However, air-cooled condensers pay a penalty in terms of

- Unlike cooling towers which use the wet bulb temperature as a heat sink, the end process temperature achievable with air-cooled condensers is higher since air cooling uses dry bulb temperatures as the heat sink. Table 6.2 shows that typically the dry bulb temperatures are

Table 6.2 Wet and dry bulb temperatures for some selected European cities

City	Wet bulb temperature		Dry bulb temperature	
	°C	°F	°C	°F
Athens	22	71.6	36	97
Berlin	20	68	29	84
London	20	68	28	82
Paris	21	69.8	32	90
Rome	23	73.4	34	93

8°–14° more than the corresponding wet bulb temperature. They also have a higher approach temperature range of 10° C–15° C

In practice, air-cooled condensers are used in manufacturing plants when the process temperatures are greater than 70° C–80° C, such as in oil refineries. Given these constraints, air-cooled systems are less efficient than comparable wet cooling systems.

- As mentioned in Chapter 5, in cooling towers the primary cooling mechanism is due to the evaporation of water given the high latent heat of water (2431 kJ/kg). Sensible cooling only plays a secondary role. However, in air-cooled systems, only sensible cooling can be used for cooling. Moreover, the specific heat capacity of air is four times as low (1 kJ/kg K as against water 4.2 kJ/kg K). It also suffers from a lower heat transfer coefficiency. Therefore, for the same heat transfer duty, air-cooled systems require more air flow and larger heat transfer area. For this reason they require a greater fan capacity to deliver more air and more space.

Despite these disadvantages, air-cooled systems still have a place in cooling systems. The decision to install an air-cooled chiller or condenser needs to be considered by giving due consideration to the following:

- minimising energy usage
- minimising heat emissions
- minimising plume emissions
- minimising noise emissions
- minimising water discharged to the environment
- minimising the risk of *Legionella*.

In some cases other factors may override the relatively higher cost and energy inefficiency of air-cooled chiller/condensers such as the risk of *Legionella*.

Sydney Water commissioned a study [6] to ascertain the breakeven point for the operation of air-cooled chillers versus water-cooled chiller for air-conditioning systems in commercial buildings. Figure 6.4 shows that over a 25-year life cycle, air-cooled systems were technically and financially economical at cooling loads below 450 kWR (128 Ref Tons). Archibald [7] who looked at a number of scenarios arrived at similar conclusions.

6.3.2 Hybrid Cooling Towers

Hybrid cooling towers (HCTs) utilise the best features of both air-cooled and water-cooled systems, selecting the most water- and energy-efficient mode to suit the operating and ambient conditions.

Another advantage of HCTs over cooling towers is that they eliminate the issue of plume when operating in the dry mode. This is especially advantageous in populated areas where plume formation is popularly (and falsely) associated with energy wastage or air pollution.

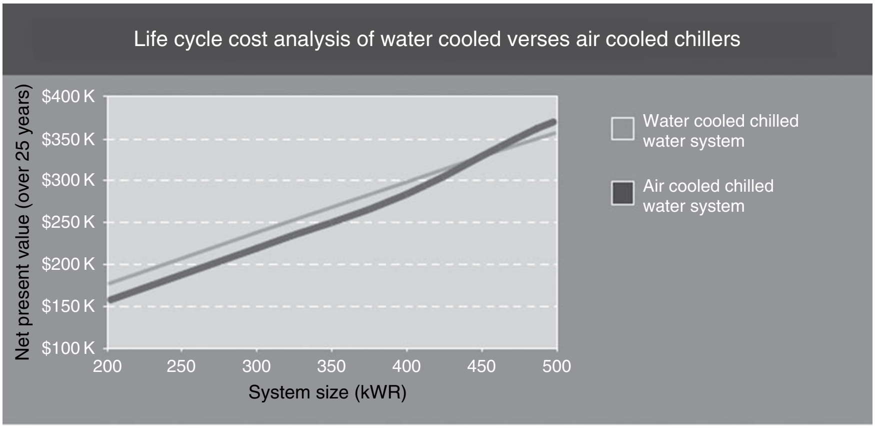

Figure 6.4 Life-cycle analysis of water-cooled and air-cooled chillers

Courtesy of Sydney Water, *Best Practice Guidelines for cooling towers in commercial buildings*, 2004.

Several competing hybrid concepts are now available on the market, each with its own advantages and disadvantages. Most can operate in two or three modes. The different modes of operation are as follows:

- **Dry mode**, in which the HCT operates essentially as an air-cooled condenser or cooler, with no water usage. Heat is rejected by warming of the air, that is only sensible cooling takes place.
- **Evaporative pre-cooled mode**, in which water is used to pre-cool the air before it reaches the heat exchange surface either as spray cooling or as closed adiabatic cooling. However, except during low humidity ambient conditions this mode can consume more water than conventional cooling water systems, at comparable cooling water or condensing temperature conditions.
- **Evaporative cooling mode**, in which the water is used to wet the surface of the heat exchange surface directly. Heat is rejected by evaporation of the water in contact with the heat exchanger. In this mode it acts as a conventional cooling tower.

In the dry/wet mode both sensible and evaporative (latent heat) heat transfer modes are used. During the cooler periods only the dry cooling tower section is used. Compared to conventional evaporative cooler significant water savings can be obtained at peak conditions.

These systems are generally more expensive than conventional air-cooled condensers/fluid coolers. Therefore, a life-cycle costing needs to be carried out to assess their cost savings over a 15-year period.

Figure 6.5 shows the Baltimore Aircoil HXI cooler which also incorporates a finned coil section at the top of the tower to eliminate plumes.

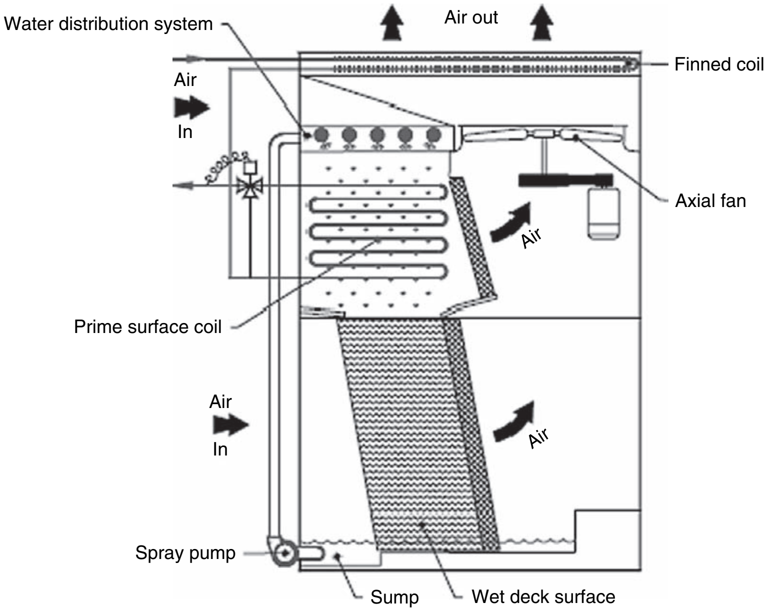

Figure 6.5 Baltimore Aircoil HXI Cooler

Courtesy of Baltimore Aircoil.

Figure 6.6 shows a cost comparison between a HXI cooler, which uses the combined technology, and that of conventional open recirculating cooling tower. While the capital cost is about four times that of a conventional cooling tower, the operating cost is only a fraction of conventional technologies.

An important consideration in the selection of a hybrid cooling system is the switch point, which is defined as the maximum air temperature at which design cooling capacity can be achieved with dry operation. For Sydney conditions a low switch point of some models generally below 14° C will dictate wet operation for a substantial portion of the year. Therefore a higher switch point 22° C gives a much longer dry operation window, and potentially greater water savings.

The HCTs systems do have operational issues such as the need to control micro-organisms through use of biocides; some models may scale up with time. To overcome the scaling problem, some designs incorporate a reverse osmosis membrane plant to spray only demineralised water on to the coils.

6.3.3 Combination Cooling Systems

Under certain conditions, a combination of evaporative and air-cooling can present a technically and commercially viable alternative to the use of either technology alone.

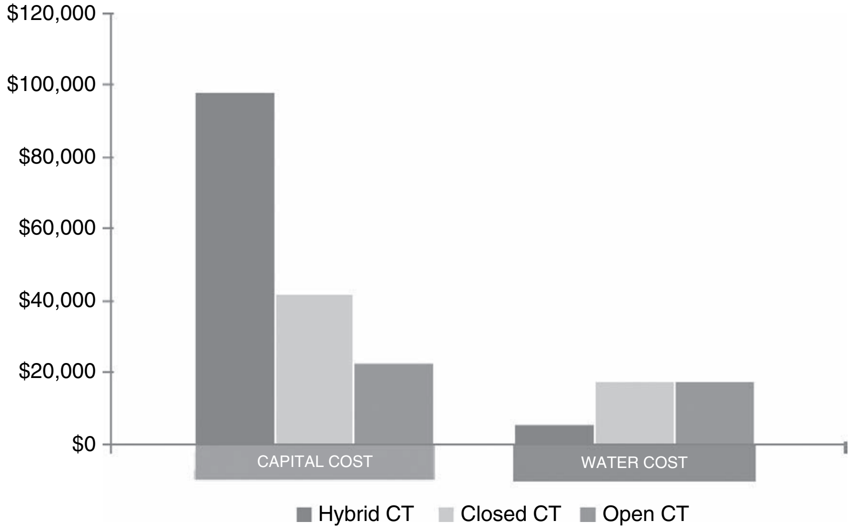

Figure 6.6 Cost comparison between HXI hybrid cooling towers and conventional wet cooling systems [8]

Comparison is based on a cooling load of 2030 kW, an inlet temperature of 40° C, an outlet temperature of 30° C and a wet bulb temperature of 24° C.

Courtesy of Baltimore Aircoil.

Generally evaporative cooling, be it an evaporative condenser or a cooling tower, is a low-capital and energy-efficient form of heat rejection. Air-cooling and especially dedicated hybrid cooling systems are far more costly. In many cases installing separate air-cooling systems in parallel to conventional evaporative cooling systems offers both energy and water savings by operating the air-cooled systems during low-ambient temperature and low-load conditions, and the evaporative during high load and high ambient only.

An analysis of typical Sydney ambient conditions shows that approximately 60% of the year, the ambient dry bulb temperatures are below 18° C, and hence well suited to air-cooling. Considering that in many cases a large proportion of the remaining 40% of the year would coincide with low load conditions, this would make air-cooling viable for as much as 80% of the year, whilst the remaining 20% would be served with evaporative cooling, with significant water savings and little or no energy penalty.

Several case studies have shown that in many cases the installation of separate air-cooled and evaporative condensers can be cheaper than a single hybrid unit only, whilst offering similar water and energy savings.

Another attractive advantage of combination systems is the redundancy achieved through the installation of dual systems. In the event that either system should fail, the other can be run, albeit at a water or power consumption penalty, until repairs have been undertaken.

The use of a combination of air-cooled and water-cooled systems has the following disadvantages:

- Significant space is required to install both systems. This is not often available.
- An intelligent control system, programmed to suit the specific design of the plant, is required to ensure that the optimum mode of operation is selected at all times.

Case Study: Red Lea Chicken, Sydney, Australia

Red Lea Chicken is a family-owned business that started in 1957. It processes in excess of 300 000 chicken a week. They decided to upgrade their system and opted for air chilling rather than use a spin chiller. This required additional cooling load. Instead of installing an evaporative condenser, Red Lea decided to install a large air-cooled condenser thus obviating the need for water use. They also installed water sprays on the condenser to cater for those hot days > 45° C (113° F) without the need for pre-cooling pads; installed variable speed control for the fans as well as a heat exchanger to recover waste heat up to 600 kW at a temperature of 60° C (140° F) that can be used as wash down water.

The decision to use air chillers resulted in a water saving of 200 m^3/day.

Adapted from: Sydney Water. *Red Lea returns on $3 million investment. The Conserver*. Issue 10. May 2006.

6.3.4 Geothermal Cooling Systems

In geothermal cooling systems, the earth is used as the heat sink. Whilst ambient air temperatures vary widely over a calendar year, 2 m below the earth's surface, the temperatures are fairly constant at 10° C–15° C range (50° F–60° F). Consequently, the earth is cooler than ambient temperatures during the warmer months and in winter it is warmer than the ambient temperature. This aspect is used in geothermal systems. In summer, the ground loop acts as a 'heat sink', rejecting the unwanted building heat. In winter, it acts as a 'heat source', absorbing heat from the ground to heat the building.

Geothermal cooling systems consist of piping loops, pumping system, condenser and air-handling units. The piping loops are filled with water and an antifreeze solution. Cooling loops made from high-density polyethylene are installed either vertically or horizontally depending on the geological formation and available land area.

If adequate land area is available without hard rock formations, then horizontal piping loops are more cost effective. These are found in open fields or under car parks. In the horizontal loop system, trenches are dug to an average depth of 1.2–1.8 m (4–6 ft). The length of the loop piping is dependent on ground temperature, thermal conductivity of the soil, soil moisture and system design.

In commercial buildings or educational facilities, vertical loops are more common due to lack of space, or is too rocky. To install a vertical loop, holes are bored 45–76 m (150–250 ft) into the ground. Long, hairpin-shaped U loops of pipe are then inserted. The hole is backfilled and cemented, the pipes are connected to headers in a trench leading back to the building. The drilling depth is determined by the lowest total cost based on the conditions at the job site. If the depth required is excessive, then multiple loops are used. A bore might have a heat rejection of 6 kW.

Geothermal systems can also utilise an aquifer, a lake, sea water or any other large body of stationary or flowing water. These are more cost effective since no drilling is required.

Case Study: Water Police, Sydney installs a geothermal cooling system [9]

The Water Police in Sydney is one of the oldest police services in Australia – selected for its new headquarters at Cameron's Cove (on Sydney's famous harbour) a geothermal cooling system for its two-storey 1500 m^2 (16 146 ft^2) headquarters.

Similar to HCTs, the capital costs for geothermal systems are initially more expensive than conventional cooling systems due to the high cost of drilling. However, operational costs are lower because they save water, energy and discharge no emissions to the environment. Energy savings are due to the fact that no external energy source is required for cooling. The compressors in the individual heat pump units of a geothermal unit operate much more efficiently than those in air-source units because the geothermal source/sink temperature is far more stable than that outdoor air and has much less severe high and low extremes.

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