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WHY EVERY AIR COOLED STEAM CONDENSER NEEDS A COOLING TOWER

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By Luc De Backer and William M. Wurtz

ABSTRACT

This technical paper will review the basic types of cooling systems utilized by utility power plants, and explain the reasons why it is advantageous to include a cooling tower in many dry cooling applications.

A system where a cooling tower is used in conjunction with an air cooled steam condenser is called a parallel condensing system. This type of system utilizes three traditional types of heat exchangers: a cooling tower, an air cooled steam condenser and a surface condenser.

An optimized parallel condensing system reduces both investment costs and operational costs while using a minimum amount of water.

1. INTRODUCTION

In the steam cycle of a power plant, low-pressure water condensed in the steam condenser is pumped to high pressure before it enters the boiler or Heat Recovery Steam Generator (HRSG) where superheated steam is produced. The superheated steam is sent to the steam turbine where the steam expands to low pressure providing the energy to drive a generator. This low-pressure steam has to be condensed in a condenser in order to complete the steam cycle.

The condensation of steam requires a cooling medium. Traditionally, this has been achieved using water from a river, a stream, a pond or seawater. The cold water is pumped through a heat exchanger and the warm water is discharged back to the water source. This is called ONCE THROUGH cooling system.

A once through system is an open loop system. The need to reduce the vast amount of water requires a closed loop system. Thus the WET COOLING system came into effect, and soon after the DRY COOLING and HYBRID COOLING systems (see Table 1). In a wet cooling system, water is circulated to condense the steam in the same type of heat exchanger that is used in the once through cooling. The warm water, instead of being rejected to the water source, is cooled in a cooling tower using air as the cooling medium. Only the water carried away due to evaporation, drift and blow-down needs to be replenished by make-up water.

Cooling System	**Time period**
Once Through	From 1930s
Wet Cooling	From 1950s
Dry	From 1970s
Hybrid	From 1980s
Parallel	From 1990s

Table 1: Evolution of cooling systems used in power plants [R1]

2. WET COOLING SYSTEMS

The wet cooling tower system is based on the principle of evaporation. The heated cooling water coming out of the surface condenser is cooled as it flows through a cooling tower, where air is forced through the tower by either mechanical or natural draft.

In the United States, the natural draft tower, sometimes also called the hyperbolic tower because of its shape, has most often be used at nuclear plants and large coal-fired power plants. Natural draft cooling towers are primarily suited to very large cooling water quantities. The advantage of a natural draft unit is that the power required for fans is eliminated; these are very tall structures (up to 600 feet in height).

In smaller power plants, all wet cooling towers are mechanical draft cooling towers, where the air flow is accomplished by fans (see figure below).

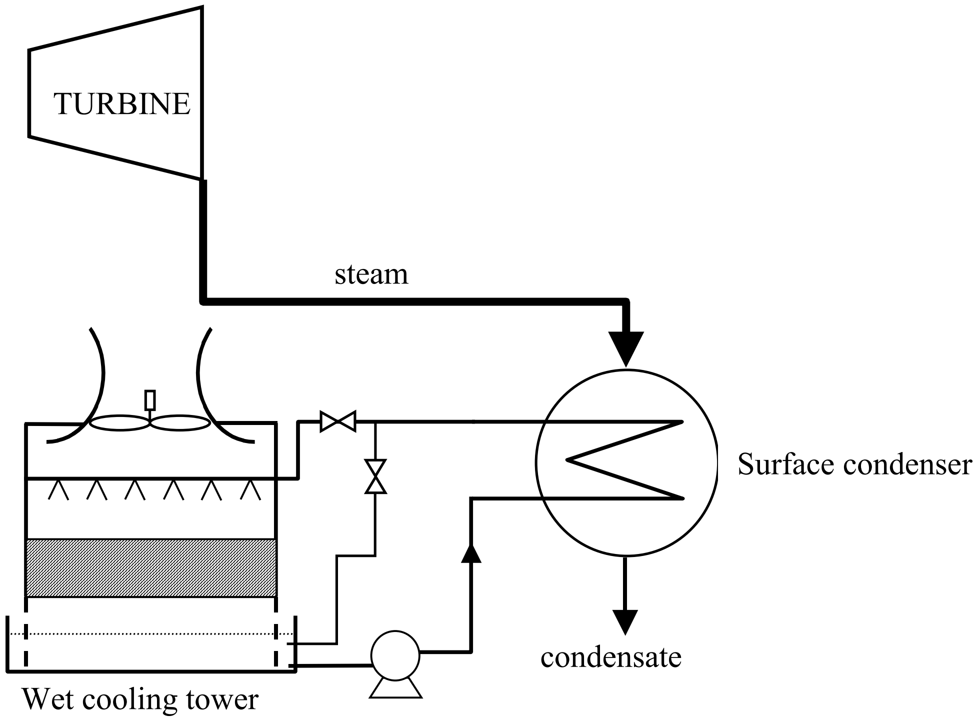

Figure 1: Indirect cooling system with a wet cooling tower and surface condenser.

The steam turbine is not directly connected to the cooling system, so this is in fact an indirect cooling system. The steam from the steam turbine is condensed at the outside of the surface condenser tubes, using cold water coming from the cooling tower. Part of the cooling water is evaporated in the cooling tower, and a continuous source of fresh water (makeup water) is required to operate a wet cooling tower.

Makeup requirements for a cooling tower consists of the summation of evaporation loss, drift loss and blow-down.

2.1 Evaporation losses:

Evaporation losses can be estimated using the following equation:

$$m'_{evap} = 0.00095\, \mathrm{m'_{cool}}\, (\mathrm{T_{hot}} - \mathrm{T_{cold}})$$

where m'_{cool} = cooling water flow rate at the tower inlet
T_{hot} = cooling water temperature at tower inlet in °F
T_{cold} = cooling water temperature at tower outlet °F

2.2 Drift:

Drift is entrained water in the tower discharge vapors. Drift loss is a function of the drift-eliminator design, and a typical value is 0.005 % of the cooling water flow rate. New developments in eliminator design make it possible to reduce drift loss below 0.0005 %. Drift contains chemicals from circulating water.

Below a typical drift drop size spectrum is shown for a counter-flow cooling tower using a modern type of drift eliminator [R2].

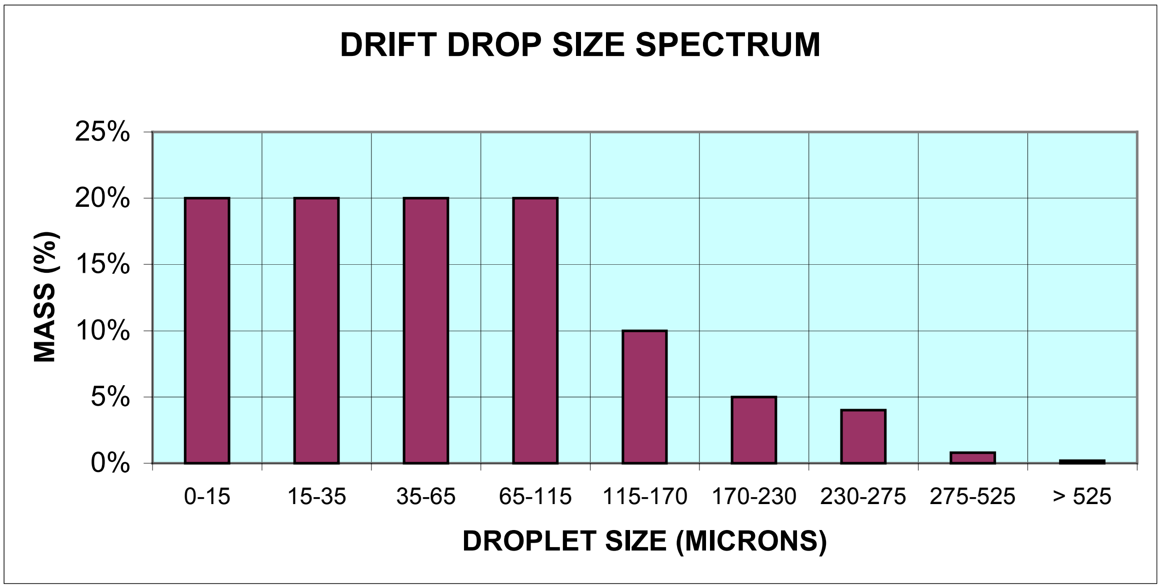

Figure 2. Cooling tower drift drop size spectrum [R2}

2.3 Blow-down:

The amount of blow-down can be calculated according to the number of cycles of concentration required to limit scale formation. Cycles of concentration are the ratio of dissolved solids in the recirculation water to dissolved solids in the makeup water. Cycles of concentration involved with cooling tower applications typically range from three to ten cycles. The amount of blow-down can be estimated from the following equation:

$$m'_{blowdown} = \frac{\mathrm{m'_{evap}}}{(\mathrm{cycles - 1})}$$

2.4 Typical water consumption examples:

As an example, a 600 MW coal fired plant operating at 70 % annual capacity factor typically would require between 5 x 10^6 m^3 and 1 x 10^7 m^3 of make-up water annually [R3]. The make-up water requirements for nuclear and geothermal plants are even higher.

For a combined cycle power plant, the make-up water requirements will be generally less than half of those for a fossil-fuelled plant of comparable size, since only one third of the total electrical output is generated in the steam cycle. Below a typical example for a cooling tower in a combined cycle plant with 2 gas turbines and 1 steam turbine:

- Heat duty = 410.9 MW or 1,402 Mbtu/h
- Water flow = 36,340 m^3/h or 160,000 gpm
- Range = 9.83 K or 17.69 deg F
- Cold water temperature = 33.1 deg C or 91.5 deg F

The equations written above give the following results:

- Evaporation loss = 611 m^3/h or 2689 gpm
- Drift loss (assuming 0.005 %) = 1.82 m^3/h or 8 gpm
- Blow-down (assuming 10 cycles of concentration) = 68 m^3/h or 299 gpm
- Total make-up water required = 681 m^3/h or 2996 gpm

Fogging, icing of local roadways and drift that deposits water or minerals are some of the concerns regarding the plume. The plume is in fact the condensed water that evaporated from the cooling process. Thus, this condensed water is pure and free of chemicals and minerals, although a plume is often associated with pollution. Other environmental effects of cooling towers and technological solutions to reduce the impact on the environment have been discussed in detail elsewhere [R4].

Sometimes because of the chemical content of the make-up water the blow-down cannot be discharged outside of the boundaries of the power plant. This is the case in power plants with “zero-discharge” requirements. But complete elimination of water consumption in the cooling system can only be achieved by using dry cooling systems, or air cooled condensers.

3. DRY COOLING SYSTEMS

In a dry cooling system, heat is transferred from the process fluid, steam, to the cooling air via extended surfaces or fin tube bundles. The performance of dry cooling systems is primarily dependent on the ambient dry bulb temperature of the air. Since the ambient dry bulb temperature of the air is higher than the wet bulb temperature (wet bulb is the basis for a wet cooling tower design), dry cooling systems are less efficient. Although the capital cost of a dry cooling system is usually higher than that of a wet cooling system, the cost of providing suitable cooling water and other operational and equipment expenses may be such that the dry cooling system is more cost effective over the projected life of the power plant.

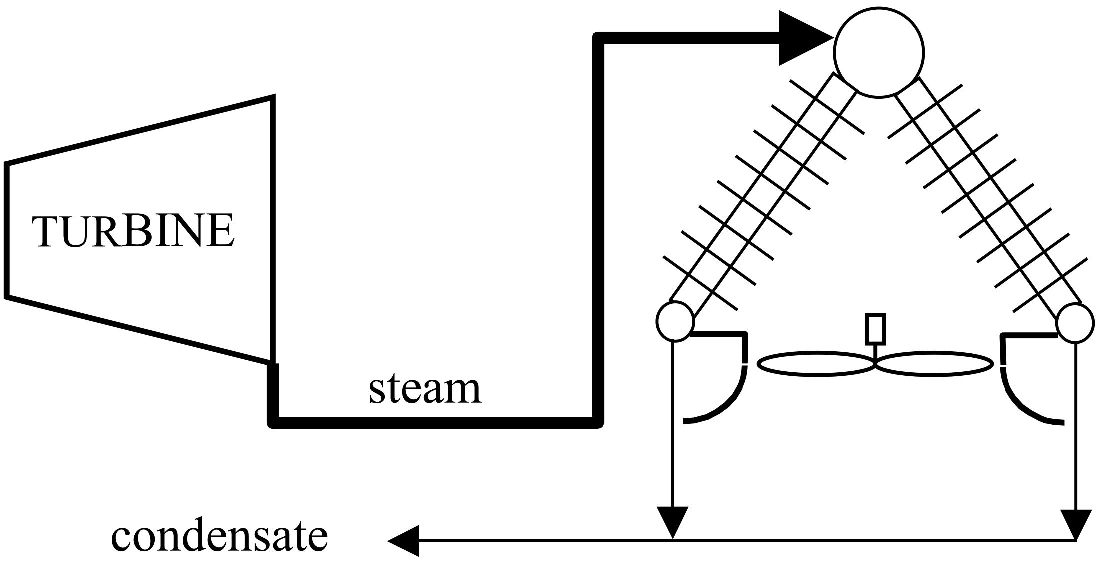

Figure 3: Dry cooling system connected to steam turbine (direct system).

In dry cooling systems, the turbine exhaust is connected directly to the air cooled steam condenser (that is why it is called a direct system) as shown in Figure 3. The steam exhaust duct has a large diameter and is usually as short as possible to reduce pressure losses. The finned tubes are arranged in the form of an A-frame to reduce the required plot area. The advantages and disadvantages of dry cooling systems are shown in table 2 below.

ADVANTAGES OF DRY COOLING	DISADVANTAGES OF DRY COOLING
Can be located at fuel source	Large plot area required
No water required	Less efficient
No plume formation	Generates more noise
No impact on environment	
Less permitting required	

Table 2: The advantages and disadvantages of dry cooling systems

Recent studies indicate that on average, one third of the new power plants permitted in North America will require a dry cooling system. This is driven by the lack of water, PM10, and EPA 316(A) and 316 (B) issues. PM10 is one of the seven air pollutants the Environmental Protection Agency (EPA) regulates under the National Ambient Air Quality Standards (NAAQS). PM10 is defined as particulate matter (PM) with a mass median diameter less than 10 micrometers. EPA standards require the PM10 concentrations (expressed in the weight of particulate matter in a cubic meter of air) to remain within certain limits.

The PM10 concentration limits (24 hour and annual allowable average) are:

- A 24 hour average not to exceed 150 micrograms per cubic meter of air more than three times in three years
- An annual arithmetic average not to exceed 50 micrograms per cubic meter of air

EPA also regulates the cooling water systems at electric generating plants and manufacturers through sections 316(a) and 316(b) of the Clean Water Act. Section 316(a) requires EPA to ensure that a cooling water system has not caused or will not cause by continuing to operate, appreciable harm to the balanced indigenous community; and allows a facility to demonstrate that thermal limitations under state quality regulations are more stringent than necessary to protect the population of shellfish, fish and wildlife in and on the body of water into which the discharge is made. Section 316(b) of the Clean Water Act requires EPA to ensure that the location, design, construction and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact.

In some areas of the US, dry cooling will be the system of choice. In the state of Massachusetts for example, air cooled condensers are used in 70 % of the recently built power plants.

4. WET/DRY OR HYBRID COOLING SYSTEMS

Wet/dry or hybrid systems designed primarily for plume abatement are essentially wet towers with just enough dry-cooling added to reduce the relative humidity of the combined effluent from the wet and dry section below the point where a visible plume will form under cool and high relative humidity conditions.

The atmospheric criteria for plume abatement are contrary to the criterion for heat rejection. In other words, the hybrid tower when operating in plume abatement mode has a lower cooling capacity compared with pure wet mode operation. However, since part of the heat rejection occurs in the “dry” section of the hybrid tower during the in plume-abatement mode, its water consumption is reduced slightly.

Generally, a hybrid tower is designed to dissipate approximately 20 to 40% of the total heat load in the “dry” section to meet the atmospheric criteria for plume-abatement, but it operates in plume-abatement mode for less than fifty percent of the time, thus reducing water consumption by 10 to 20%. On an overall basis, the reduction of water consumption in a hybrid cooling tower over the course of the year is usually limited.

5. SELECTION CRITERIA BETWEEN DRY COOLING SYSTEMS AND WET TOWERS

Since a wet tower has a lower capital cost and has a better performance in hot weather, it will be the best choice if sufficient water is available at reasonable cost. But even if enough water is available, some other factors may play a role as well. At times of high humidity and cool air temperature, a wet cooling tower is likely to produce a plume which is a visible fog exiting the tower. While the plume is environmentally safe – it is nothing but water – it can create visual problems or icing if the plant is located near a highway, residential area or airport. A power plant in Linden, New Jersey, for example went with a dry cooling system because of the twelve-lane New Jersey Turnpike next to the plant and the effect that the plume from a wet cooling tower would have on icing and fogging, which would be unacceptable [R5].

Dry cooling saves a lot of water but there is a price to pay for it; the capital cost is significantly greater and there may be plant limitations on the hottest days. Also the heat rate may be impacted on all but the coldest days. That is why dry cooling systems need a performance enhancement during hot ambient temperatures. There are different ways to enhance the performance of a 100 % dry cooling system, and one of them is spraying water at the air inlet of the fans. The purpose of this system is to reduce the dry bulb ambient temperature as close as possible to the inlet wet bulb ambient temperature during hot and dry summer days, using evaporation of the water droplets at the air inlet. However, adding a wet tower that needs only a limited use of water during summer days is probably the most attractive available solution as will be shown in this paper.

6. THE PARALLEL CONDENSING SYSTEM (PCS)

Parallel condensing systems, have been developed to save water, while avoiding the high cost of dry cooling systems and to ensure a relatively low steam turbine back pressure at high ambient conditions.

An excessive rise in steam turbine backpressure during periods of peak ambient temperatures and demand will result in a loss of efficiency of the steam turbine-generator set. In such a case, the dry section of the system may be designed to reject the total heat load at a low ambient temperature while maintaining the turbine backpressure within specified limits at high ambient temperatures using the wet part of the system. One way of sizing the wet part of a PCS cooling system is to limit the quantity of make-up water according to the local water availability.

A PCS system is a synergy of established cooling system technologies and combines some positive features of dry and wet cooling systems; the water consumption is reduced compared to a 100 % wet system, the performance is improved compared to a 100 % dry system and the capital cost decreases as the proportion of wet in the PCS system is increased.

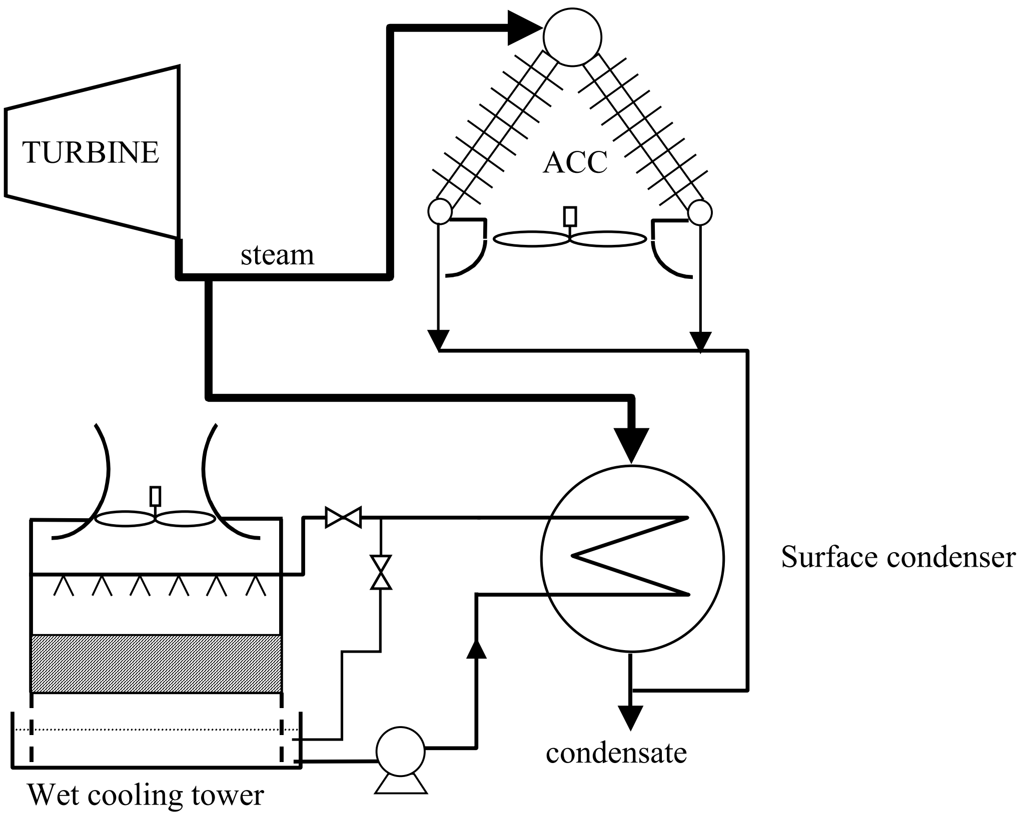

Figure 4. Parallel condensing system (Dry/wet cooling system).

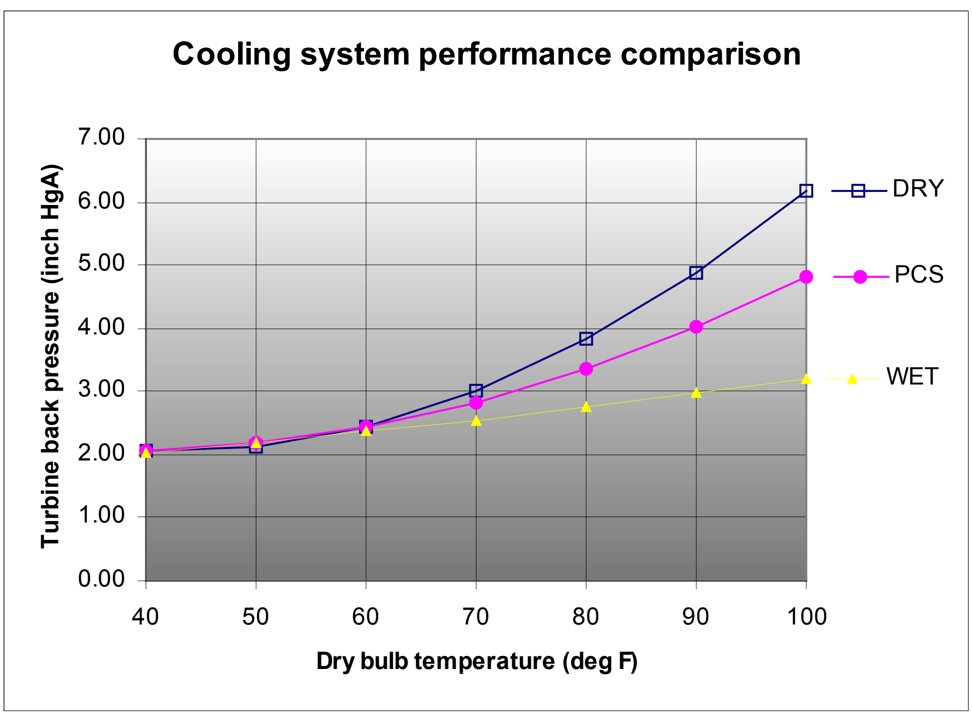

Figure 5. Dry, PCS and wet cooling systems – comparison of the performance.

A typical cooling system performance is shown in Fig 5.; the turbine back pressure is plotted as function of the dry bulb temperature. As can be noticed, all three cooling systems are similar in performance at reduced dry bulb temperatures. As the ambient temperature rises, the dry cooling system is penalized the most and will have the highest turbine back pressure.

The wet cooling system is able to maintain a much lower turbine back pressure at high ambient temperatures. The performance of the PCS system is in between the dry and wet cooling systems. The relative improvement of the PCS system with respect to the 100% dry cooling system is dependent on the amount of water that is used for wet cooling.

Another way to express the cooling system performance, however, is to evaluate the steam condensing capacity of the condenser at the maximum ambient dry bulb temperature. For simplicity, only a qualitative comparison is shown in table 3 below.

STEAM CONDENSING CAPACITY	COOLING SYSTEM
100 %	WET
Up to 100 %	PCS
Less than 100 %	DRY

Table 3. Steam condensing capacity of the wet, PCS and dry cooling systems.

The steam condensing capacity in this context can be defined as the amount of steam that can be condensed by the steam condenser in order to avoid a steam turbine trip, 100 % being full load. The advantage of the PCS system over the 100 % dry system is obvious. In a situation where the load to the steam turbine has to be reduced at high ambient temperatures with a dry cooling system, a PCS system can be designed in such a way that the steam turbine can operate at full load without risk of a steam turbine trip on a hot summer day. Under these design conditions, the air cooled condenser alone would not be able to avoid a steam turbine trip at full load and maximum ambient conditions.

In the following example we will show that by using some water for a wet cooling tower, the capital investment can be reduced significantly compared with a dry cooling system.

DESIGN CONDITIONS	VALUE in SI units	VALUE in US units
ambient dry bulb temp	40.6 deg C	105 deg F
relative humidity	16%	16%
ambient wet bulb temp	21.0 deg C	69.8 deg F
atmospheric pressure	946 mbar	27.9 inch HgA
required thermal duty	445.4 MW	1521120739 BTU/hour
turbine back pressure	< 270 mbar	< 8.0 inch HgA

Table 4. Design conditions for the air cooled condenser and PCS system.

A 100 % dry cooling system and a PCS system (using a small cooling tower) were designed for the design conditions that are shown in the table 4.

The major requirement is to avoid a turbine trip (typical value is a turbine back pressure lower than 270 mbar or 8 inch HgA) at the maximum ambient air temperature. In the following study it was decided to design the PCS system in such a way that the wet cooling tower should only operate on hot summer days (ambient dry bulb temperature above 32 deg C or 90 deg F).

In the parallel condensing system, the wet cooling tower can be shut down in spring, autumn and winter, because the dry portion of the cooling system is sufficient to handle the required thermal duty. In the graph below it can be noticed that the dry portion of the PCS system can handle the thermal duty up to an ambient temperature of about 32 degrees Celsius (90 deg F).

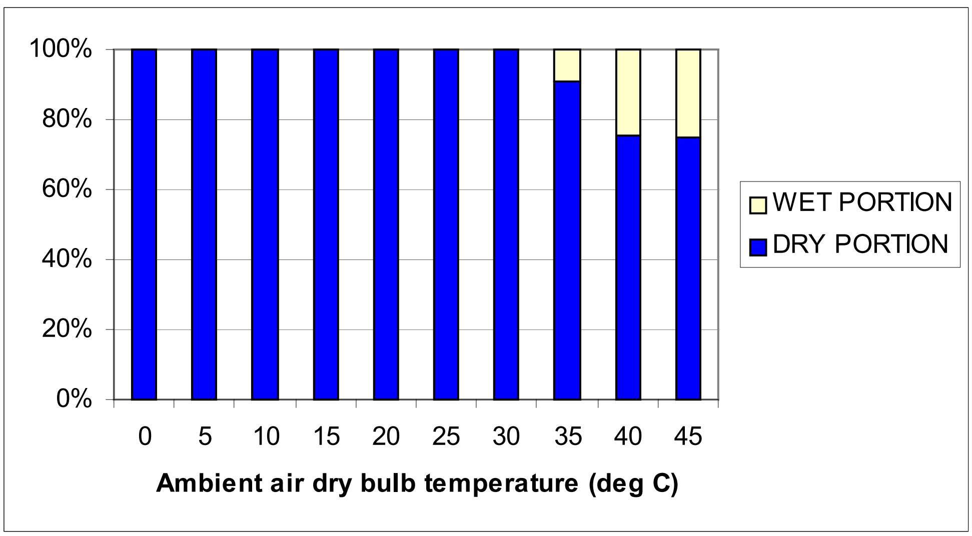

Figure 6. Wet and dry portion of the thermal duty as function of ambient dry bulb temp.

As the ambient air temperature rises, a larger portion of the duty is handled by the wet cooling tower. At the maximum ambient dry bulb temperature, the wet cooling tower rejects about 25 % of the total thermal duty.

The monthly average temperature distribution that we used in our example is given in the graph (Fig. 7). Assuming that the air cooled condenser cannot handle the thermal duty any more for ambient air temperatures exceeding 32 °C (89.6 °F), combined with the temperature distribution from Figure 7 it is assumed that the wet cooling tower will be working for only about 30 days per year, which is a reasonable design for a PCS system.

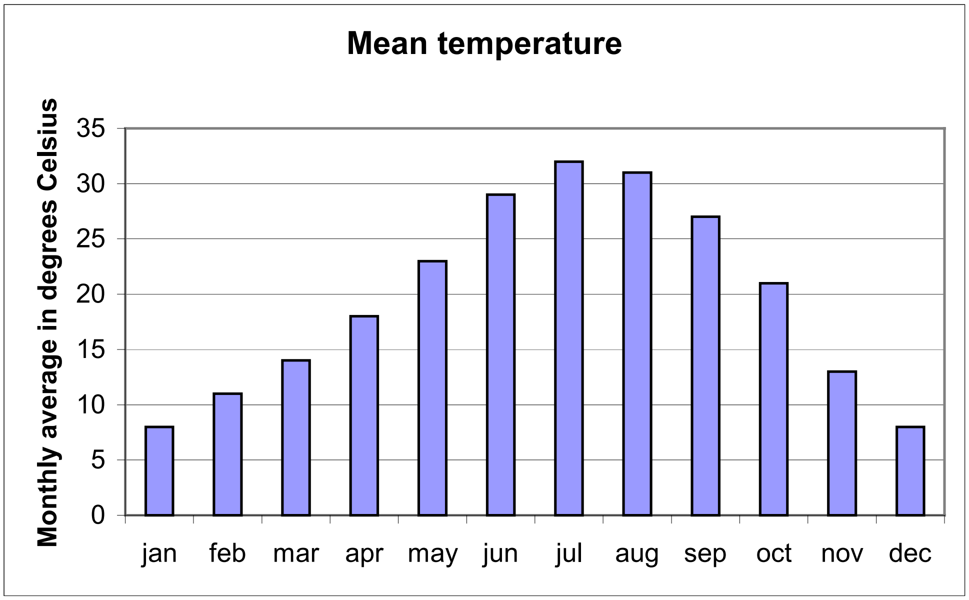

Figure 7. Monthly average temperature for the PCS system design.

Using the equations above, an estimate of the amount of make-up water that is required to operate the wet cooling tower for one month per year can be done. Assuming a drift of 0.005 % and 5 cycles of concentration for the blow-down, we arrive at a make-up flow of about 68 kg/s (1080 gallons per minute).

Considering a cost of water of $2.00 per 1000 gallons of water, the predicted yearly cost for make-up water should be about $100,000. The cost of water in an all wet system would be $3,000,000 per year (using 3000 gpm make-up during 350 days a year).

An estimation of the capital costs for the wet part of the PCS cooling system is based on the following breakdown [R6], as shown in table 5:

ELEMENT	COST
Wet cooling tower	35 - 45 % of system cost
Installation/erection	included in base price
Surface steam condenser	35 - 45 % of system cost
Tower basin	3 - 6 % of system cost
Electricals and controls	Typically $25,000 per cell
Circulating water system	5 % of system cost
Water treatment/blowdown dischar	1 % of system cost

Table 5. Capital cost breakdown for the **wet part** of the PCS cooling system.

The capital cost of the air cooled condenser (reference value = 100 % dry cooling) includes the cost for installation and erection, and is estimated at about $31.2 million for a typical 500 MW combined cycle power plant.

Table 6 compares the PCS system and an air cooled condenser (100 % dry) for capital cost, plot area and fan power consumption. The figures assume that the cooling water pumps (estimated at about 500 hp pump power) and the fans of the wet cooling tower are only operating for about one month per year.

ITEM	ALL DRY SYSTEM	PCS SYSTEM
dry fraction of heat	100	73%
capital	100	79%
fan power	100	83%
plot	100	82%

Table 6. Comparison between air cooled condenser and PCS system.

As can be noticed from table 6, the introduction of a small cooling tower (typically two cells) can reduce the capital cost by more than 20 % compared to a 100 % dry system (remark: a 100 % dry system refers to a cooling system where an air cooled condenser is responsible for one hundred percent of the total heat duty). Also the plot area and fan power consumption are more favorable for the PCS system. Operational costs are expected to be less for the PCS system in general.

7. CONCLUSION

Because of restrictions on thermal discharges to natural bodies of water, almost all power generating plants or large industries requiring cooling will require closed cycle cooling systems. Evaporative or wet cooling systems (cooling towers) generally are the most economical choice for closed cycle cooling systems where an adequate supply of suitable water is available at reasonable cost to meet the make-up requirements of these systems. If only the plume is an issue the solution may be a wet/dry cooling system (hybrid cooling towers). But although these systems may save some water, the amount of make-up water is still significant and a plume will still be present under certain atmospheric conditions, and this may be unacceptable if the power plant is close to a major highway or airport.

If only a limited amount of water is available, or the water cost is too high, most power plants tend to go for a 100 % dry system without considering the PCS system. In some cases, a dry cooling system has been selected even if water is available at reasonable cost where political or environmental considerations prevail. But by selecting a parallel cooling system that is designed to use the available water for a cooling tower on hot summer days, the performance of air cooled condensers can be enhanced and significant savings on the capital and operational costs of the cooling system can be expected. Moreover, the wet cooling tower can be shut down most of the time (except on hot summer days), so the negative effects of a plume (fogging and icing in winter months) are not an issue.

8. REFERENCES

R1: Comparison and optimization of cooling systems for coal fired plants, Ram Chandran and William Wurtz, paper presented at Coal-Gen 2002.

R2: Wet/dry cooling towers for plume abatement and water conservation, Paul A. Lindahl Jr., presented at the Air & Waste Management Association Symposium, San Diego – Ca, May 2002.

R3: Air-cooled steam condensers and dry and hybrid cooling towers, Detlev G. Kroger, Power-Gen competitive power college 111, Orlando – Fl, November 2000.

R4: The latest worldwide technology in environmentally designed cooling towers, by Gary R. Mirsky, Jean-Pierre Libert, Kathy Briant and Franz Bouton, presented in technical paper number TP92-02, and the 1992 CTI annual meeting in Houston – Tx.

R5: Power cooling primer, by Patricia Lloyd Williams, Independent Energy, Jan 1993.

R6: Wet and dry cooling – cost/performance tradeoffs, by John S. Maulbetsch, presented at the Air & Waste Management Association Symposium, San Diego – Ca, May 2002.