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# WATER CONSUMPTION OF COOLING TOWERS IN DIFFERENT CLIMATIC ZONES OF THE U.S.

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## ABSTRACT

Cooling towers are widely used across a range of industries and represent the largest reuse of water in industrial and commercial applications. While continually recycling water, cooling towers loose significant inventory through evaporation and blowdown.

The local climate strongly affects the efficiency of a cooling tower and its water consumption. This paper discusses the performance of cooling towers in different climatic zone of the U.S. considering the seasonal variations of outdoor air temperature, wind speed and solar radiation. The analyses are carried out with the Sargent & Lundy's software suite UHS which simulates the transient heat and mass transfers occurring in cooling tower/basin systems.

## 1. INTRODUCTION AND PURPOSE OF THE ANALYSIS

The National Climatic Data Center has identified nine climatically consistent regions within the contiguous United States [1] as shown in Figure 1.

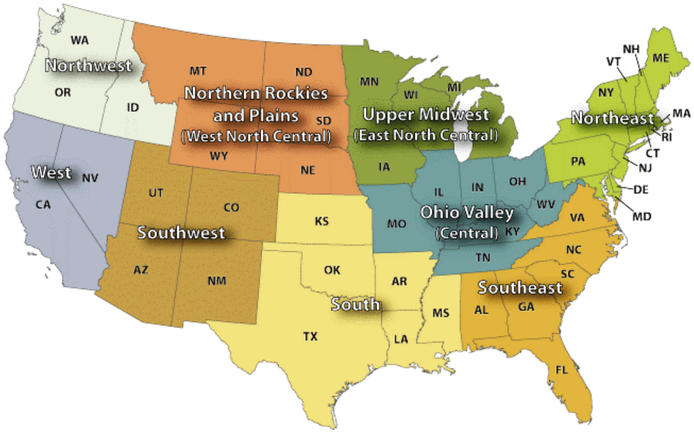

**Figure 1 – U.S. climatic regions as defined by NCDSC/NOAA**

This paper reports the results of the simulations for three identical cooling tower/basin systems located in the Southeast, Upper Midwest and Southwest regions of the U.S.A. between May 1st and October 31st. The average evaporation rates from the cooling tower and the basin surface along with the transient results are compared for the three sites and the effects of wind and solar insolation are estimated.

## 2. HISTORICAL BACKGROUND OF UHS

In 1985, the U.S. Nuclear Regulatory Commission funded a project led by Dr. W.E. Dunn of the University of Illinois at Urbana-Champaign for the development of a computer model to be used in the design and analysis of the cooling tower/basin system of ultimate heat sinks for nuclear power plants. The UHS suite of codes developed for this project is documented in a thesis by Susan Marie Sullivan, which was submitted as partial fulfillment of the requirements for her Master of Science in Mechanical Engineering degree [2, 3]. This suite was later used in the U.S. NRC safety evaluation reports for the Vogtle and River Bend nuclear stations. The original version of the UHS suite only determined the impact of the cooling tower on the basin. Since many other heat and mass transfer processes can affect the mass, temperature and salinity of the basin, the original program was expanded into a Sargent & Lundy LLC version. As explained in the following sections, various features and enhancements were added to the code. In addition, steam and air thermo-physical properties were updated to use more recent correlations. Furthermore, historical weather data are now retrieved directly from various environmental centers.

## 3. TECHNICAL FEATURES OF UHS

The purpose of the Sargent & Lundy's UHS suite of programs is to provide the user with tools for predicting the time dependent temperature, mass and dissolved solid content of power plant heat sinks that consist of a basin and one or more cooling towers [4]. The code considers the cooling tower heat and mass transfer analysis coupled with the mass and energy balance for the basin. It is flexible enough to be applied to many different sites and it takes into account basin make-up, blowdown, seepage, pipe leakage, evaporation, solar radiation and basin wall heat conduction/convection. All of these processes are typically part of the circulating water systems with cooling towers.

UHS consists of four modules: Weather Search, PDAP, Surface Solar and UHSsim.

### 3.1 Weather Search Module

Per the Regulatory Guide 1.27 [5], the meteorological conditions considered in the design of the heat sinks should be selected with respect to the controlling parameters and critical time periods unique to the specific design of the sink. For cooling towers and the associated basin, two distinct controlling meteorological conditions can be identified: conditions resulting in maximum cooling water temperature or maximum evaporation rate. The meteorological conditions resulting in minimum water cooling (maximum water temperature) may not correspond to the meteorological conditions resulting in maximum evaporation and drift losses (i.e. dry bulb temperature, wet bulb temperature, wind speed and solar radiation).

Weather Search can scan several decades of historical hourly weather data to find the period of minimum cooling or the maximum evaporation. A number of improvements have been incorporated into the original code. The module has now several user options that allow the identification of conservative historical time windows based on instantaneous values, running averages, maximum evaporation potential or specific tower/basin system time constant, which represents the time response of the basin to external influences. Either a sliding or folding window technique can be specified which provides significant flexibility in analysis of the data. These improvements provide the Sargent & Lundy's version of the code with increased capabilities for finding the periods of highest evaporation over large time spans. When going through several decades of weather data, average values can first be used to identify the worst years. Next, more detailed methods can be used to narrow down the worst evaporation window. Finally, a third confirmatory run can be performed with more specific methods such as the tower/basin system time constant or cooling tower performance. The identified worst weather period(s) is used to predict the basin conditions based on actual heat loads and system characteristics. For this paper, weather data for two typical years are used since the purpose of this study is to compare average evaporation rates for three regions of the U.S.A.

### 3.2 PDAP Module

The UHS suite allows the simulation of cooling tower performance in two alternate ways: if vendor curves for the range of conditions under investigation are available, they can be directly entered as input in a tabular format, otherwise the Merkel method is applied. This last method allows predicting the cooling tower performance at conditions which are not otherwise available. PDAP, the Performance Data Analysis Program, is used to find the Merkel coefficient (KAV/L) for the cooling tower that best fits the available cooling tower data. A number of improvements have been incorporated into the original code including updated thermodynamics properties (ASME's steam tables, ASHRAE's air and water tables), steam pressure evaluation in proximity of the water free surface, convergence enhancement and error minimization of the Merkel coefficient (KAV/L) estimation. The number of computational nodes within the tower can be increased to improve the accuracy of the Merkel model and guarantee mesh independent results. This version of the code allows ensuring the convergence in each of the tower elements with a pre-selected accuracy rather than just the last element. An option for a diagnostic output was added which is used to check the intermediate results of the computations. An additional option is added to allow the far field air wet-bulb temperature read from weather data to be increased to account for local air recirculation from the tower outlet.

### 3.3 Surface Solar Module

Surface Solar is used to compute time dependent solar radiation (direct, diffuse and reflected) on the basin's walls and water surface. The solar insolation is calculated using measured data, the ASHRAE methodology [6] or the Midwest Agricultural Weather Center [7] methodology. The algorithm accounts for the site location (longitude and latitude), weather conditions, the orientation and emissivity/absorptivity of the basin surfaces and the time of the year. Radiation back the sky is also calculated considering a weather-dependent sky emissivity. This option is helpful in simulating the heat loss to the sky from the basin surfaces during day and/or night time when additional conservatism is required. This module is an entire new addition to the UHS suite.

### 3.4 UHSsim Module

UHSsim is used to simulate the change in mass, temperature and salinity of the cooling tower basin. It integrates the results from the Weather Search, PDAP and Surface Solar modules along with the plant heat load, the circulating water system configuration and the basin specifications to predict the heat sink performance over time.

A number of improvements have been incorporated into the original code including the following. Input for UHSsim now consists of two text files. The input data file contains parameters that specify calculation options, system lineup, tower design data, tower operating characteristics, tower analysis data, initial basin properties, plant heat rejection data and specification of other processes that affect the basin mass, temperature and salinity. The weather data file contains the ambient weather conditions for the time period to be analyzed (dry bulb and wet bulb temperature, atmospheric pressure, wind speed, solar radiation, sky cover, etc.).

The code resolves the differential equations for the heat and mass balance of the basin and cooling tower. Options are available to account for the basin natural and forced evaporation, solar heat load and radiation heat loss from the basin surfaces, convection and conduction heat loss from the basin walls, seepage, pipe leakage, make-up and blowdown. A limited number of these features were present in the original version of the code and are addressed in Reference 2. Most of the newly added features are straightforward and are not discussed further here. Heat loss through the basin walls is a more complex new feature and thus is addressed here. Each wall is divided into a series of nodes which are used to solve the transient one-dimensional heat conduction. The energy balance on the interior surface is solved based on time-varying convection to or from the basin water. The exterior surface allows heat transfer through various mechanisms. Convection to or from the outdoor air is calculated for either still conditions or wind. Solar heating and sky radiation can also be invoked. If wall radiation is invoked, the Surface Solar Module is used to calculate the heat gain or loss. The temperature changes are numerically integrated to find the transient temperature profile across the wall. The heat transfer at the inner surface adds or removes heat from the basin water. The improvements to the original code make UHSsim flexible enough to be applied to many different plant layouts and sites.

### 3.5 Steps of the UHSsim Analysis

The first step in the analysis is the estimation of the Merkel coefficient for the simulation of the cooling tower. This coefficient is computed using the data from the vendor performance curves at various air and water flow rates. For every combination of air and water flow rates, the PDAP module automatically computes the corresponding Merkel coefficient by minimizing the prediction error from the vendor data. The obtained Merkel coefficients are used as inputs in the UHS module to simulate the tower when paired to the basin. This provides a significant flexibility in the analysis since the operation of the cooling tower can be estimated at flow rates different from those specified in the vendor curves. Alternatively, the vendor curves can be used directly in the analysis. This solution is ideal for the simulation of specialized types of cooling tower designs (mechanical and natural draft, cross-flow, counter-flow, hybrid, etc.).

Next, the weather data from various environmental centers are processed to identify the period of time corresponding to the maximum cooling tower evaporation or minimum cooling capability. This step is not performed in the analysis documented in this paper since its intent is to investigate the difference in water loss between May 1st and October 31st in various climatic regions the United States. Hourly weather data for two random years, 1970 and 1990, are used and compared to ensure that the results are consistent and can be considered to be typical to each of the analyzed region.

Finally, the input file for UHSsim is assembled to compute the time-dependent evaporation rate for the tower/basin system including the effect of solar insolation and forced evaporation due to wind. The results are calculated and printed out with a specified time frequency. For this study, the results are reported hourly, consistent with the frequency of the weather data.

## 4. UHSsim MODEL

The system analyzed in this paper includes one counterflow cooling tower and one basin. Figure 2 shows the layout of the system.

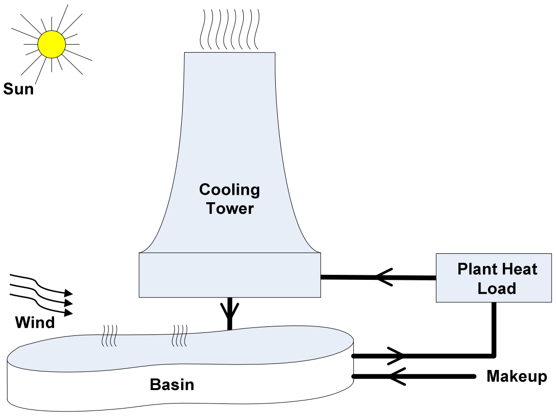

**Figure 2 – Layout of the cooling tower/basin system**

In order to simplify the analysis, fresh water makeup is considered in the system (zero solid content) and seepage, pipe leakage and blowdown are not modeled. Furthermore, the plant heat load and basin makeup flow are kept constant through the simulations.

The following sites are selected as representative for the U.S. Southeast, Upper Midwest and Southwest regions, respectively: Tallahassee FL, Waterloo IA and Tucson AZ. Following are the design characteristics of the system:

Cooling Tower Design Characteristics

- Water flow rate: 16,500 gpm;
- Water inlet temperature: 116°F;
- Water outlet temperature: 93°F;
- Cooling range: 23°F;
- Inlet humid air flow: 4,526,280 lb/hr;
- Inlet air dry-bulb temperature: 98°F;
- Inlet air wet-bulb temperature: 81°F;
- Atmospheric pressure = 14.7 psia;
- Outlet air dry-bulb temperature: 106°F;
- Outlet relative humidity: 100%;
- Approach temperature: 12°F;
- Drift loss: 0.01% of inlet water flow;
- Water to air flow ratio (L/G): 1.8053;
- Merkel coefficient (KAV/L): 1.6843;
- Heat load: 55.1 MW (thermal);
- Evaporation loss: 334 gpm;
- Evaporation based on water latent heat of vaporization = 380 gpm.

Basin Design Characteristics

- Initial basin mass: 7,204,000 gallons;
- Initial basin temperature: 60°F;
- Surface size: 32,000 ft$^2$;
- Makeup water flow rate: 230 gpm at 60°F.

For the purpose of this study, the following cooling tower operating conditions are considered:

Cooling Tower Operating Conditions

- Water flow rate: 13,820 gpm (83.8% of design);
- Humid air flow: 4,472,000 lb/hr (98.8% of design);
- Water to air flow ratio (L/G): 1.5239;
- Merkel coefficient (KAV/L): 1.7427;
- Heat load: 38.1 MW (thermal).

## 5. RESULTS

As a first rough estimate, the cooling tower evaporation rate is typically computed dividing the plant operating heat load by the water latent heat of vaporization. This is due to the fact that, in a cooling tower, the heat load is rejected by evaporating some of the circulating water flow. However, the value computed in this manner does not account for the sensible heat transfer between the water and air streams. Depending on the air inlet conditions, this value could be more or less accurate. Furthermore, it may not be always conservative as shown below. For the cooling tower operating conditions listed above the evaporation rate so computed is equal to 126,213.6 lb/hr. This value is considered to be the baseline value for all of the results reported in this paper.

Table 1 shows the average evaporation rates from the cooling tower and the basin surface for the three analyzed sites between May 1st and October 31st. As seen, for all three sites, the tower evaporation is less than the baseline by approximately 10% to 25%. This is due to the sensible heat loss to the air stream as indicated above. The results also show that the tower evaporation is less in the Upper Midwest region where the average air dry-bulb temperature is lower. On the other hand, the tower evaporation is higher in the Southwest region where the air is hotter and drier. Although dependent on the specified Merkel coefficient (see Section 4), the relative magnitude of these results can be extended to cooling towers of different sizes. Note also that the initial basin temperature does not significantly impact the conclusions of this study since its effect is lost after few days into the simulation. Table 1 also shows the contributions to the basin evaporation rate due to the wind and solar insolation. As seen, the solar effect tends to be higher than the wind effect. Differently from the cooling tower, these results cannot be generalized since they are strongly dependent of the basin design characteristics, namely the basin surface area and depth. In fact, the solar heat gain, which affects the basin water temperature, is directly proportional to the surface area. However, it can be inferred from the results in Table 1 that these effects are rather small.

| Average | Waterloo, IA | Tallahasse, FL | Tucson, AZ |
|---|---|---|---|
| **Tower** | 76.3% | 80.8% | 88.5% |
| **Basin - Solar** | 0.6% | 0.9% | 1.2% |
| **Basin - Wind** | 0.2% | 0.1% | 0.2% |
| **Total** | 77.1% | 81.8% | 89.9% |

**Table 1 – Average evaporation rates as a percentage of baseline.**

| Minimum | Waterloo, IA | Tallahasse, FL | Tucson, AZ |
|---|---|---|---|
| **Tower** | 57.8% | 65.0% | 70.0% |
| **Basin - Solar** | 0.0% | 0.2% | 0.9% |
| **Basin - Wind** | 0.0% | 0.4% | 0.1% |

**Table 2 – Minimum evaporation rates as a percentage of baseline.**

| Maximum | Waterloo, IA | Tallahasse, FL | Tucson, AZ |
|---|---|---|---|
| **Tower** | 99.9% | 99.7% | 117.9% |
| **Basin - Solar** | 1.3% | 1.0% | 1.8% |
| **Basin - Wind** | 1.6% | 1.5% | 0.2% |

**Table 3 – Maximum evaporation rates as a percentage of baseline.**

Tables 2 and 3 report the minimum and maximum hourly evaporation rates recorded during the simulations. As seen, in a colder environment, the tower evaporation can be as low as approximately 60% of the baseline value. On the other hand, it can be up to approximately 20% higher in a very hot and dry environment. This is due to fact that the inlet air dry-bulb temperature may be higher than the value at the outlet of the tower, i.e. the entering air stream is cooled down by the water stream as it flow through the initial portion of the tower.

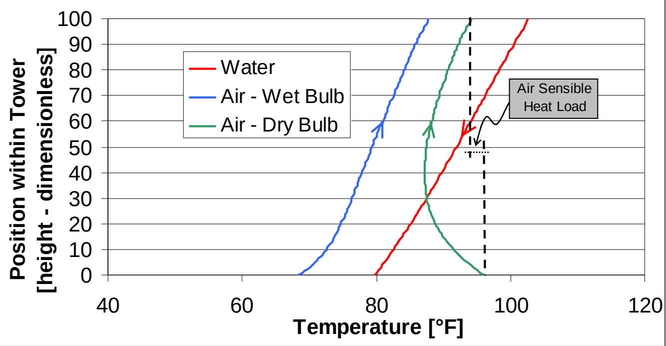

**Figure 3 – Water and air temperature distributions within the tower in the case of total evaporation more than baseline.**

Figure 3 reports the water and air temperature distributions within the cooling tower for this case. As seen, while the wet-bulb temperature is constantly increasing through the tower, the dry-bulb temperature initially decreases until its value is approximately equal to that of the water stream. From that point on, the dry-bulb temperature increases until it exits the tower. However, as the air dry-bulb temperature is lower at the outlet than at the inlet, the air stream has been effectively cooled down by losing sensible heat to the water stream thus causing an increased water evaporation rate. Figure 4 reports an example of the water and air temperature distributions within the cooling tower when the total evaporation rate is less than the baseline. As seen, in this case, the air dry-bulb temperature constantly increases through the tower helping the cooling of the water stream.

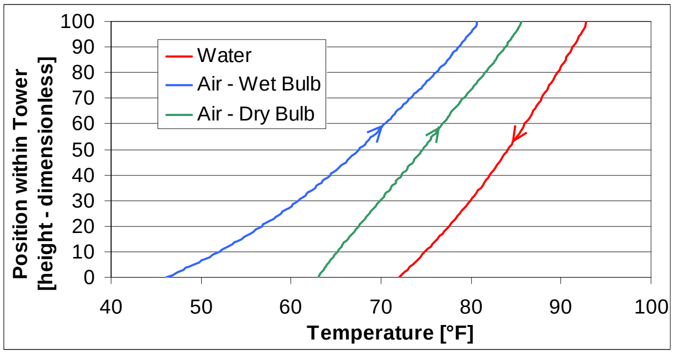

**Figure 4 – Water and air temperature distributions within the tower in the case of total evaporation less than baseline.**

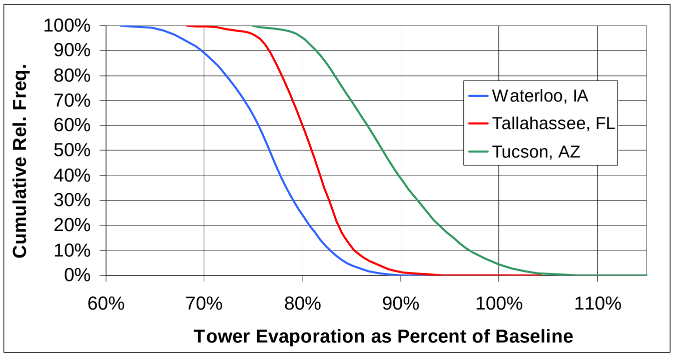

**Figure 5 – Cumulative frequency of the tower evaporation rate between May 1st and October 31st.**

Figure 5 shows the cumulative frequency of the tower evaporation rate between May 1st and October 31st. Even in the case of the hot and dry Southwest region, the evaporation rate is above the baseline only approximately 5% of the time, i.e. 9 non-consecutive days in 6 months. In the Southeast and Upper Midwest regions, the tower evaporation is practically never above baseline.

## 6. CONCLUSIONS

This paper reports expected cooling tower evaporation rates for the U.S. Southeast, Upper Midwest and Southwest regions between May 1st and October 31st. It has been shown that, on average, the evaporation rate is approximately 10% to 25% lower than baseline and it can be at times higher due to the sensible heat loss of the air stream flowing through the tower which increases the total heat load on the tower. However, even in the case of the hot and dry Southwest region, the evaporation rate is above the baseline only approximately 5% of the time, i.e. 9 non-consecutive days in 6 months. In the Southeast and Upper Midwest regions, the tower evaporation is practically never above baseline. The results also show that the tower evaporation is less in the colder Upper Midwest region and higher in the Southwest region where the air is hotter and drier. In all the analyzed regions, the contributions to the evaporation rate from the basin surface due to the solar insolation and wind speed are small

## ACKNOWLEDGMENTS

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