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Operational Cooling Tower Model (CTTool v1.0)

S. E. Aleman

A. J. Garrett

January 2015

SRNL-STI-2015-00039, Revision 0

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1.0 Overview

1.1 Objective

Mechanical draft cooling towers (MDCT's) are widely used to remove waste heat from industrial processes, including suspected proliferators of weapons of mass destruction (WMD). The temperature of the air being exhausted from the MDCT is proportional to the amount of thermal energy being removed from the process cooling water, although ambient weather conditions and cooling water flow rate must be known or estimated to calculate the rate of thermal energy dissipation (Q). It is theoretically possible to derive MDCT air exhaust temperatures from thermal images taken from a remote sensor. A numerical model of a MDCT is required to translate the air exhaust temperature to a Q. This report describes the MDCT model developed by the Problem Centered Integrated Analysis (PCIA) program that was designed to perform those computational tasks. The PCIA program is a collaborative effort between the Savannah River National Laboratory (SRNL), the Northrop-Grumman Corporation (NG) and the Aerospace Corporation (AERO).

1.2 Impact

Since mechanical draft cooling towers are used widely by suspected proliferators, improvement in government sponsors' ability to derive energy dissipation rates (and production rates) from thermal imagery of the tower will improve the accuracy of the all-source analyst's assessment of the suspected proliferators' activities.

1.3 Background

This work was sponsored by the National Geospatial and Intelligence Agency (NGA). MDCT's at suspected proliferant sites often appear to be discharging small amounts of thermal energy to the environment, relative to their design specifications. The MDCT's at these sites often run for long periods with their fans off, but with warm water circulating through them. In recognition of the lack of experimental data on MDCT performance under low heat load conditions, NGA funded data collections in and around the Savannah River Site (SRS) F-Area cooling towers in 2004 and the H-Area and A-Area cooling towers in 2005. The model development described here made use of the 2004 and 2005 collections for benchmarking. The 2005 collections at SRS include counterflow and cross-flow MDCT's, whereas the 2004 collection included only the SRS F-Area counterflow MDCT. The MDCT models were updated in this work to include physics based models for induced and natural draft/wind-aided conditions. Rochester Institute of Technology sensor Look-Up-Tables (LUTs) of predicted temperature correction factors to thermal imagery of throat exhaust temperatures were incorporated into the new tool (Montanaro, 2009). Both counterflow and cross-flow MDCT's are widely used by various industries, including suspected WMD proliferators.

2.0 Model and Tool Description

2.1 Model Description

A cooling tower model that derives heat dissipation rates (Q's) from thermal imagery must make several additional calculations in addition to computing the temperature drop of the cooling water as it passes through the tower. These additional calculations are needed to convert the remotely measured cooling tower throat or area-weighted temperature into a cooling water inlet temperature. The model thus has two main components; 1) the inner model, which computes the amount of cooling experienced by the water as it passes through the tower as a function of inlet cooling water temperature and ambient weather conditions (air temperature and humidity), and 2) the outer model, which takes a remotely measured throat or area-weighted temperature and iterates on the inlet water temperature to match the target temperature of interest.

The cooling tower model produces an estimate of the rate at which energy is being discharged to the atmosphere by evaporation and sensible heat transfer (Q). The estimate of Q is based on the computed change in air or water enthalpy as it passes through the MDCT. If the MDCT fans are on, a prescribed mass flowrate of air and water is used. If the MDCT fans are off, an additional mechanical energy equation is iteratively solved for the mass flowrate of air.

Figure 1 through 3 shows the code structure of CTTool v1.0. The description of each subroutine is given in Table 1.

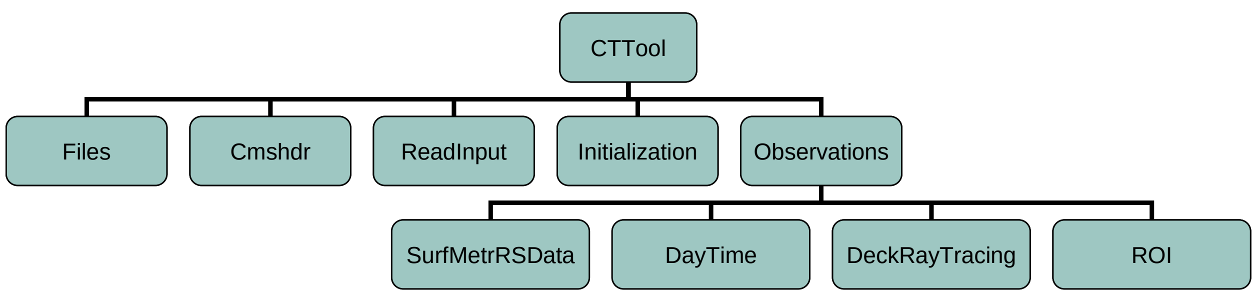


Figure 1. Main code structure of CTTool v1.0.

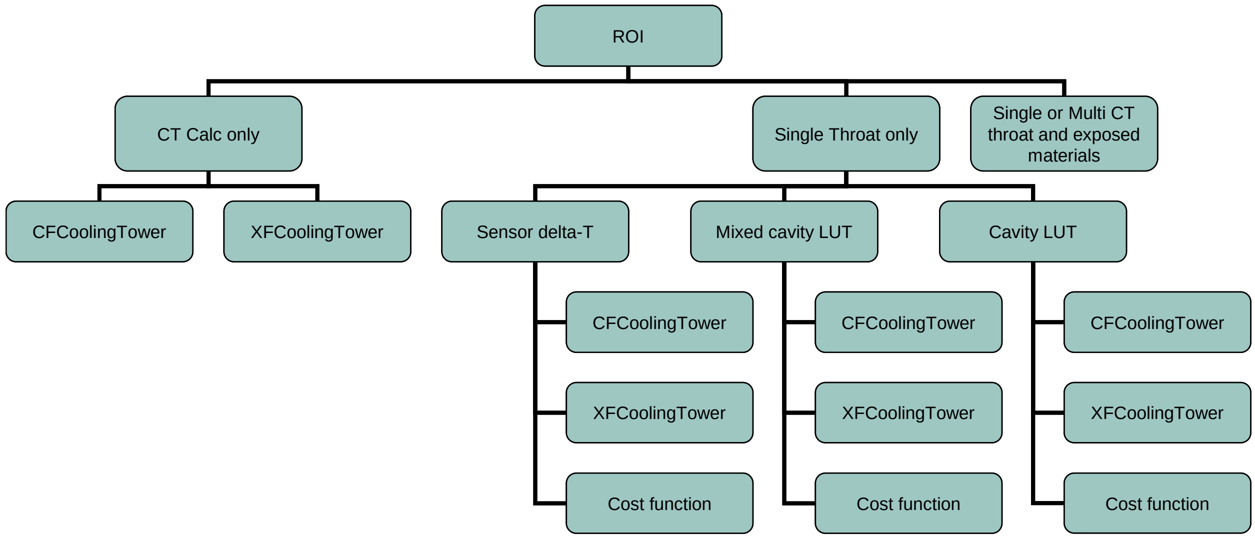


Figure 2. CTTool Region-of-Interest (ROI) code structure.

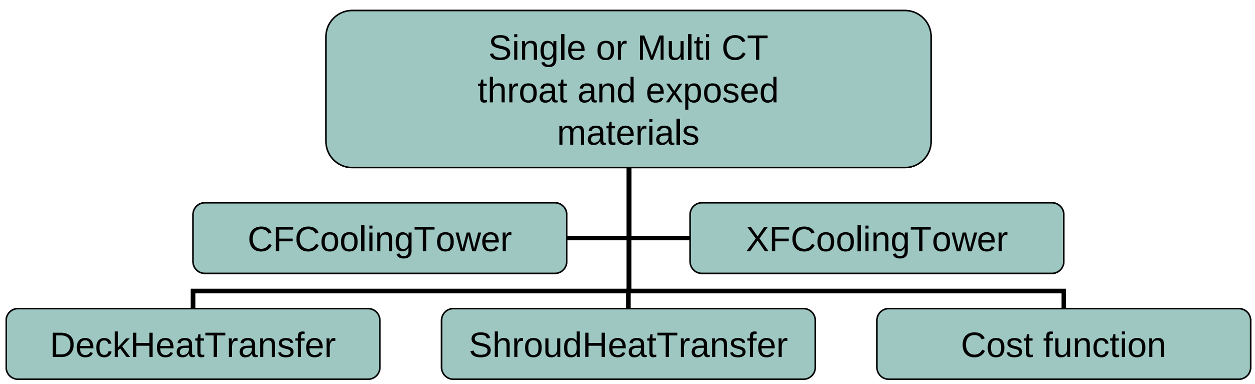


Figure 3. CTTool single or multiple cooling tower throats and exposed materials code structure.

Table 1. CTTool Subroutine Descriptions.

Program Unit	Description
CTTool	A cooling tower model that derives heat dissipation rates (Q's) from

Program Unit	Description
	thermal imagery must make several additional calculations in addition to computing the temperature drop of the cooling water as it passes through the tower. These additional calculations are needed to convert the remotely measured cooling tower throat or area-weighted temperature into a cooling water inlet temperature. The CTTool model thus has two main components: 1) the inner model, which computes the performance of a counterflow or cross-flow cooling tower during induced draft (fan on) or wind-aided/natural draft (fan off), and 2) the outer model, which takes a remotely measured throat or area-weighted that iterates on the inlet water temperature to match the target temperature of interest
Files	Reads superfile and opens files for input/output.
Cmshr	Prints the configuration management header.
ReadInput	Reads and processes all CTTool input parameters and data.
Initialization	Initializes deck ray tracing arrays. Initializes cooling tower variables and arrays.
Observations	Loops over observations or images.
SurfMetrRSData	Updates surface meteorology and remote sensing data for each observation or image.
DayTime	Converts zday and ztime to local time.
DeckRayTracing	Assigns material ids to water decks (XFCT), solid deck, exposed throat, deck hidden by fan shroud and throat hidden by fan shroud using ray tracing from sensor line-of-sight to cooling tower. The fractional areas are then computed for each material type.
ROI	Region-of-Interest. See Appendix A.
CFCoolingTower	Models the performance of an induced draft or natural draft/wind-aided wet counterflow cooling tower.
XFCoolingTower	Models the performance of an induced draft or natural draft/wind-aided wet cross-flow cooling tower.
DeckHeatTransfer	Computes the steady-state deck top surface temperature using an energy balance.
ShroudHeatTransfer	Computes the steady-state fan shroud inner and outer surface temperatures.

The following sections will describe the MDCT models in more detail.

2.1.1 Inner Model

A general numerical model, for predicting the steady-state thermal performance of wet mechanical draft cooling towers, has been developed and is herein described. The model handles both cross-flow and counterflow type cooling towers. With the fan turned-off, a cooling tower can operate in the natural draft/wind-aided mode, and the model can also predict the performance in this mode of operation. It is generally a one-dimensional model, though the heat and mass transfer in the fill sections of a cross-flow cooling tower are treated two-dimensionally. Detailed derivations and descriptions of the governing equations and constitutive relations are presented. The numerical algorithms are also described. The model is written in FORTRAN 95 with a modular structure and dynamic memory allocation. New cooling tower designs can be easily added to the software framework.

The cooling tower model simulates steady-state performance. It predicts the temperature and mass flowrate of the effluent water and the temperature and water vapor content of the exhaust air. Inputs are the temperature and mass flowrate of the incoming water and the temperature and humidity ratio of the incoming ambient air. In the mechanical draft mode the air mass flowrate is specified, and in the natural draft/wind-aided mode it is calculated.

Because of the different flow regimes in the fill sections of the two types of cooling towers, the two types are modelled separately and the model descriptions are in separate subsections. Model assumptions common to both tower types are:

- Uniform air or water temperature throughout each stream at any cross section.
- Uniform cross-sectional area of the cooling tower.
- Heat and mass transfer in the direction normal to flows only.
- Negligible heat and mass transfer through tower walls to the environment.
- Neglibible heat transfer from the cooling tower fan and motor assembly to the air.
- Air/water vapor is assumed to be a mixture of ideal gasses.
- Water droplets are assumed to be of uniform diameter.
- Water droplets fall at a constant velocity.

Mechanical draft cooling towers frequently consist of multiple units, termed cells. Figure 4 shows a cooling tower with four cells. Each cell is self-contained and they can be operated independently. The model predicts the performance of a single cell or multi-cell configurations. Counterflow and cross-flow cooling towers are described separately in the following two subsections.

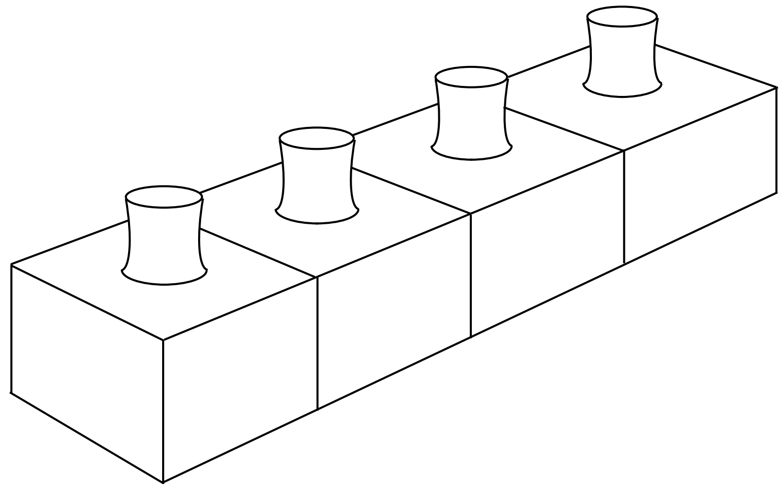


Figure. 4: Schematic of a four cell mechanical draft cooling tower.

Counterflow cooling tower

Figure 5 is a schematic of a counterflow mechanical draft cooling tower. Air enters near the bottom of the cooling tower and flows vertically upward through the fill section and the drift eliminator and exhausts through a shroud at the top which encloses the fan. Hot water enters above the fill section. A set of nozzles spray the water on the top of the fill in a manner such that the downward flow through the fill is close to uniform. The film fill consists of numerous vertical passages, each in which water flows as a falling film on the solid surface and air flows vertically upward in the interior. Heat and mass transfer occurs at the falling film free surface. Film fills are designed to maximize the water free surface area and the residence time inside of the fill section. To this end, film fills are frequently designed such that the water film follows a torturous path as it meanders downward through the fill. Below the fill section, water falls as droplets into a collection basin at the bottom of the cooling tower. Though most of the water cooling occurs in the fill section, some further cooling occurs in the rain zone. The heat and mass transfer in the rain section is negligible (for moderately sized towers) and was not modeled. The drift eliminator removes small entrained water droplets from the upward flowing air. The water basin in a cooling tower with multiple cells is generally common for all cells, with a single discharge line for the tower cooling water.

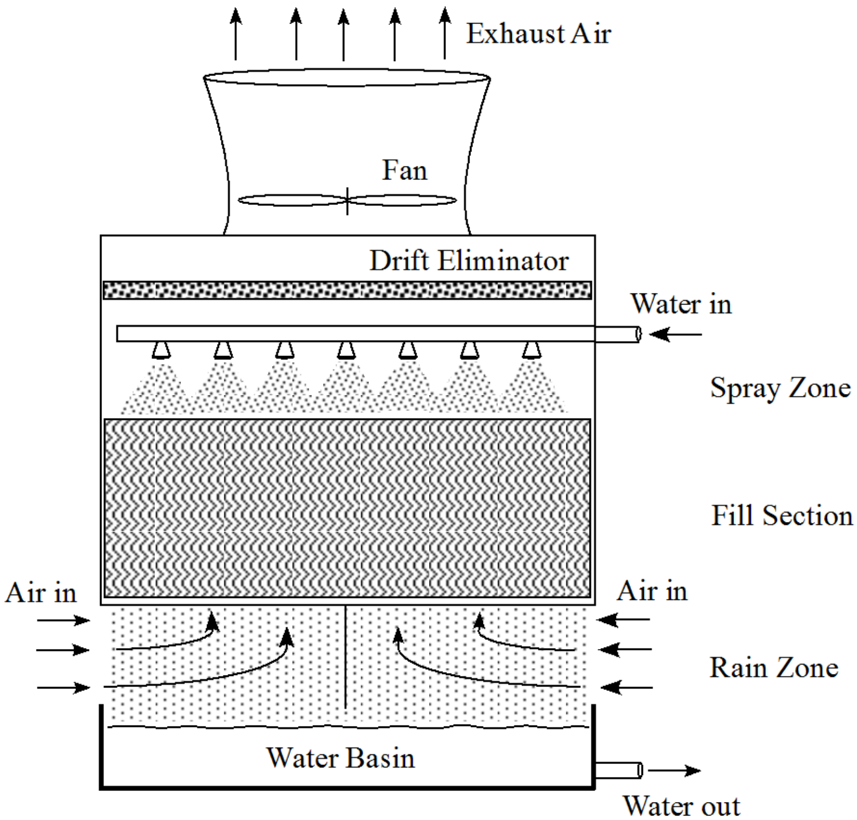


Figure 5. Schematic of a counterflow cooling tower

Flow through the cooling tower is assumed to be one-dimensional with the heat and mass transfer occurring in the fill. Heat and mass transfer is neglected in the spray zone above the fill and in the rain zone below the fill.

The fill section is divided into discrete number of stacked horizontally slice control volumes as shown in Fig. 6. An outer computational loop solves the air/water concurrent or countercurrent continuity and energy equations iteratively for the mass flowrate of water, water temperature, air temperature and humidity ratio through the cooling tower. Newton's method is used to solve for the four variables within a fill section control volume. An additional mechanical energy equation is used to solve for the mass flowrate of air through the cooling tower during natural draft/wind-aided operation (fan off).

Figure 7 is a schematic of a single control volume in the fill. During the outer computational loop the mass flowrate of water, water temperature, air temperature and humidity ratio are calculated for each control volume. The evaporation rate from the falling film for unsaturated and supersaturated air is shown in Eq. 2-1a and 2-1b, respectively. Equation 2-2 is the liquid continuity equation for the falling film. Equation 2-3 is the air/water vapor energy balance equation. Equation 2-4 is the liquid energy balance equation for the falling film. Equation 2-5 is the water vapor continuity equation. These equations and their variables are described in Appendix B.

$$\dot{m}_{ev_i} = \frac{k_m A_s M_{H_2O}}{\overline{R}} \left(\frac{P_{vs_i}}{T_{w_i}} - \frac{\omega_i P}{T_{a_i}(0.622 + \omega_i)} \right) \tag{2-1a}$$

$$\dot{m}_{ev_i} = \frac{k_m A_s M_{H_2O}}{\overline{R}} \left(\frac{P_{vs_i}}{T_{w_i}} - \frac{\omega_{s,i} P}{T_{a_i}(0.622 + \omega_{s,i})} \right) \tag{2-1b}$$

$$\dot{m}_{wi-1} - \dot{m}_{ev_i} = \dot{m}_{wi} \tag{2-2}$$

$$\dot{m}_a (C_{p,a_i}(T_{a_{i-1}} - T_{a_i}) + \omega_{i-1} h_{g,a_{i-1}} - \omega_i h_{g,a_i}) + (\dot{m}_{w_{i-1}} - \dot{m}_{w_i}) h_{g,w_i} = hA(T_{a_i} - T_{w_i}) \tag{2-3}$$

$$\dot{m}_{wi-1} h_{f,w_{i-1}} - \dot{m}_{wi} h_{f,w_i} = (\dot{m}_{w_{i-1}} - \dot{m}_{w_i}) h_{g,w_i} + hA(T_{w_i} - T_{a_i}) \tag{2-4}$$

$$\dot{m}_a (\omega_i - \omega_{i-1}) = \dot{m}_{wi-1} - \dot{m}_{wi} \tag{2-5}$$

The flow through the fill section of a counterflow cooling tower is modeled as flow between heated parallel flat plates. The expressions for the Nusselt number are shown in Eq. 2-6. Equation 2-7 is the expression for the Sherwood number.

$$\begin{aligned} Nu_d &= 8.235 & Re_d &< 2300 \\ Nu_d &= 0.00324987\,Re_d + 0.9902987 & 2300 \le Re_d &\le 10000 \\ Nu_d &= 0.023\,Re_d^{0.8}\,Pr^{1/3} & Re_d &> 10000 \end{aligned} \tag{2-6}$$

$$Sh_d = Nu_d \left(\frac{Sc}{Pr} \right)^{1/3} \tag{2-7}$$

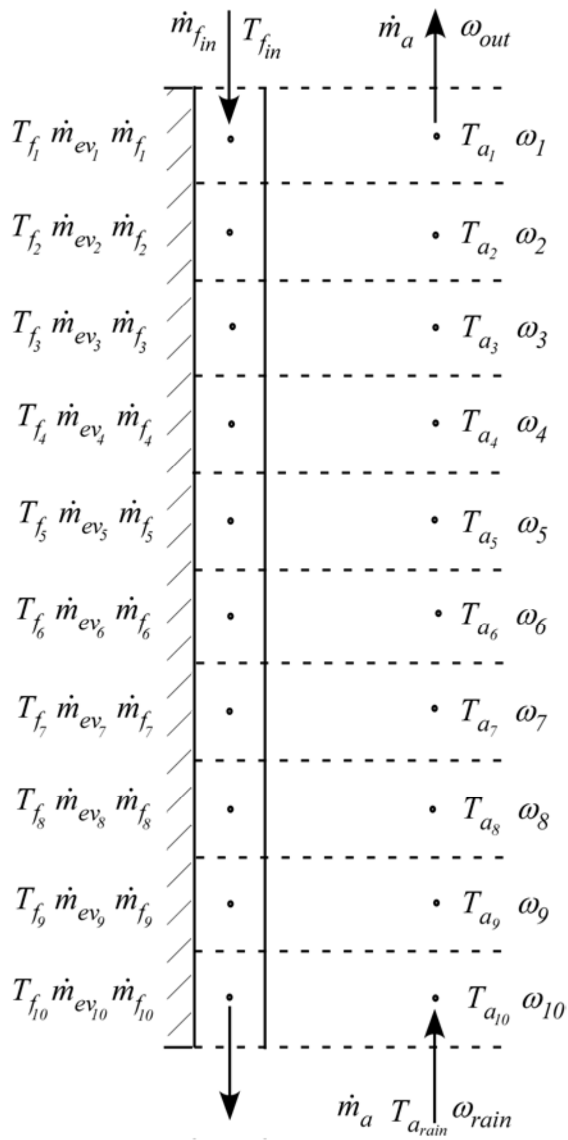


Figure 6. Schematic of the fill section showing the stacked horizontal slice control volumes.

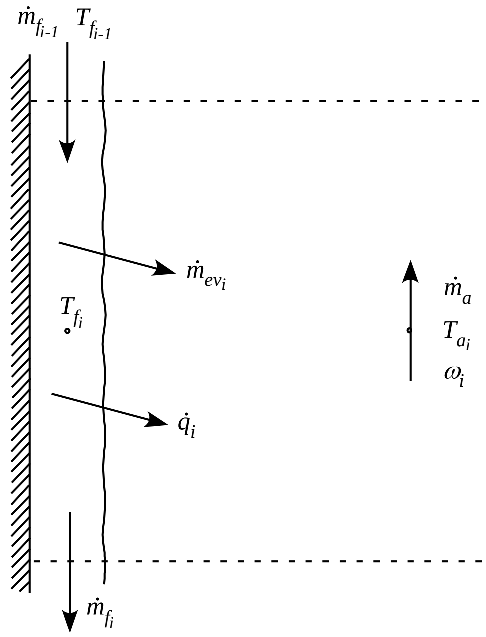


Figure 7. Schematic of heat and mass transfer between the falling water film and the rising air stream in a horizontal slice control volume of the fill section of a counterflow cooling tower.

In the mechanical draft mode, the mass flowrate of dry air is specified. With the fan off and hot water flowing through the cooling tower, air will continue to flow through the tower due to buoyancy. Wind pressure at the air inlet to the cooling tower will also enhance air flow through the tower. The air flowrate is determined from the overall mechanical energy equation for the dry air flow. Figure 8 is a schematic of natural draft/wind-aided flow through a counterflow cooling tower. Equation 2-8 is the mechanical energy equation for natural draft/wind-aided through the cooling tower, see Appendix D. The flow through the fill is assumed to be laminar flow between flat plates. Equation 2-8 is solved for the dry air flowrate iteratively by Newton's method in an outer loop that encompasses the computational loop for the fill section. A value for the flowrate is assumed and the densities in the buoyancy terms are evaluated with the model. The outer loop runs until the value of the dry air flowrate converges.

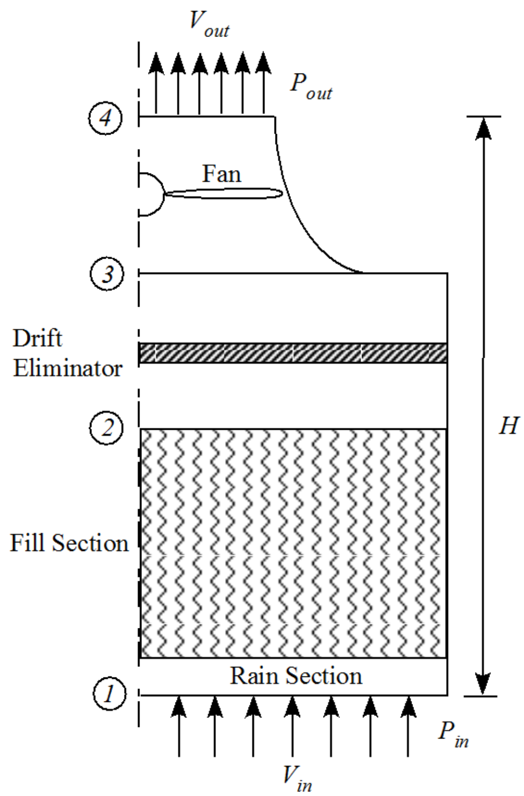


Figure 8. Schematic of natural draft/wind-aided flow through a counterflow cooling tower.

$$f = \frac{1}{2\rho}\left(\frac{1}{A_{out}^2} - \frac{1}{A_{in}^2} + \frac{K_{fill}}{A_{fill}^2} + \frac{96}{Re}\frac{L_{fill}}{D_h A_{fill}^2} + \frac{K_{2-3}}{A_{2-3}^2} + \frac{K_{3-4}}{A_{3-4}^2}\right)\left|\dot{m}_a\right|\dot{m}_a + \sum_{fill+rain}\bar{\rho} g \Delta z + \bar{\rho} g (z_4 - z_2) - \rho g H - \rho \frac{V_w^2}{2} \quad (2\text{-}8)$$

Cross-flow cooling tower

Figure 9 is a schematic of a cross-flow cooling tower. Air enters the cooling tower through the two sides, flows horizontally towards the center, and then exhausts vertically upward through a shroud. In the mechanical draft mode, the fan enclosed by the shroud pulls the air through the cooling tower. Water enters the cooling tower above the fill sections and is uniformly distributed on the tops of the two fill sections. It then flows vertically downward through the two fill sections as droplet flow and is collected in a basin at the bottom of the cooling tower. The air flow cools the falling water droplets by evaporation and sensible heat transfer. The drift eliminators remove small water droplets entrained in the air flow. A center baffle prevents wind from blowing air through the cooling tower, in one side and out the other, when the fan is not operating.

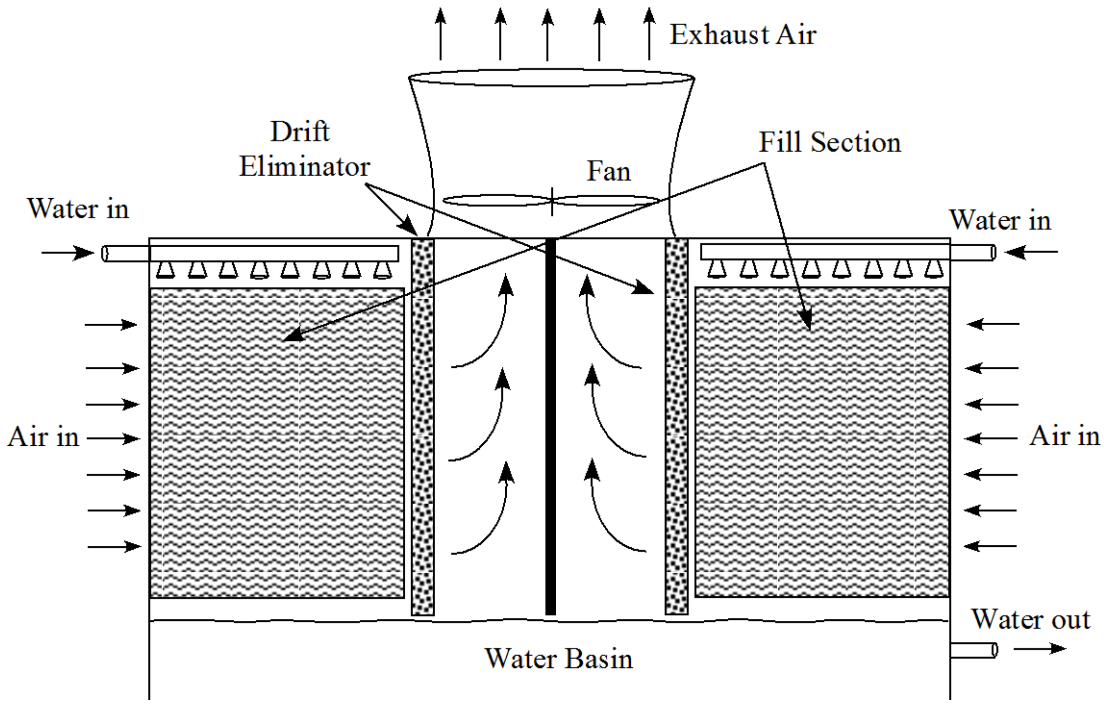


Figure 9. Schematic of a cross-flow cooling tower.

All of the water cooling occurs in the fill section of the cooling tower. Figure 10 is a schematic of the arrangement of a typical splash fill section. It consists of an array of horizontal and parallel splash bars, through which the water falls as droplet flow. The splash bars slow the falling water droplets to increase the contact time with the air flow, and continually breakup the droplets to prevent coalescence, thereby increasing the water/air interfacial surface area. For a given water flowrate, smaller droplets increase the interfacial surface area. The splash bars are staggered such that the vertical distance that a droplet can fall without interference is limited. This reduces the average droplet fall velocity and increases the contact time with the air. Heat transfer and evaporation per unit mass of water from a droplet to the surrounding air are directly proportional to exposure time and inversely proportional to the square of the droplet diameter. Air flows parallel to the splash bars and perpendicular to the direction of velocity of the falling droplets.

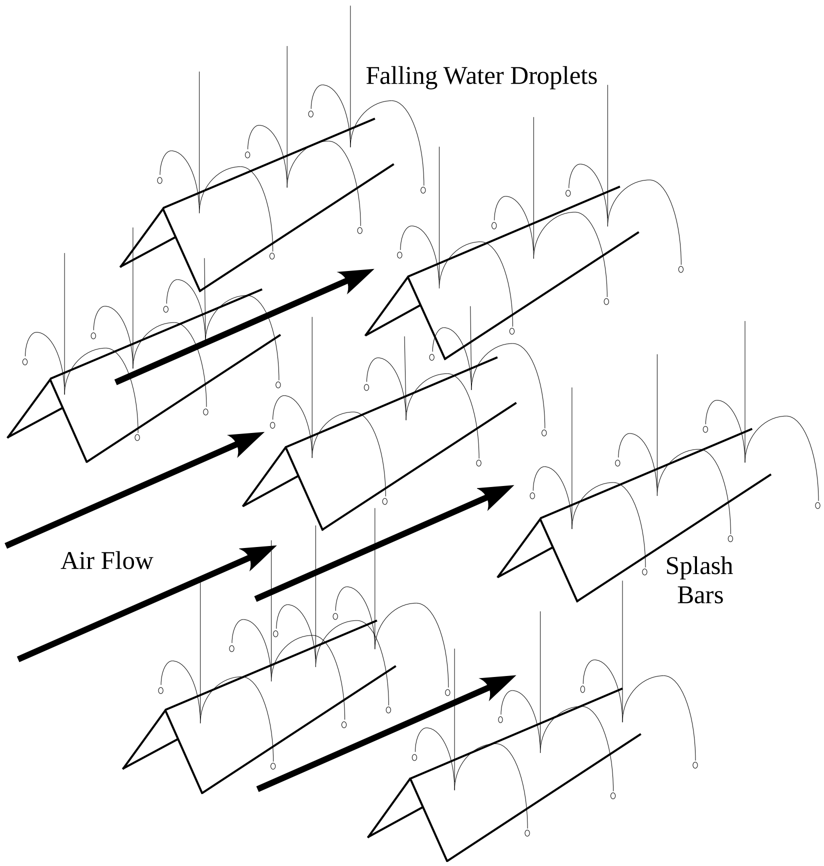


Figure 10. Typical splash bar fill structure.

Even with the assumptions of uniform inlet flow for both air and water, the flow through the fill sections is inherently two-dimensional. The water droplets cool as they drop vertically and the air is heated as it moves horizontally inward. Interfacial drag between the air and water droplets is neglected in the mechanical draft mode of operation. This considerably simplifies the model, as the mass flowrate of air is specified and a fan performance curve is not necessary. The air flow is assumed to be horizontal and parallel to the splash bars, and the water droplets are assumed to fall vertically. Phasic continuity and thermal energy equations for the two-dimensional fill section can be solved in a once-through marching scheme. Momentum equations would couple all of the fill equations and require them to be solved simultaneously.

Figure 11 shows the computational mesh representing one of the two fill sections in a cross-flow cooling tower and the once through marching scheme used to calculate the air and water flow temperature distributions. Figure 12 is a schematic of a single control volume in the fill mesh. In this marching scheme, the values of the entering flow variables to a single control volume are known and only the effluent values require calculation. The droplet density, diameter, and velocity are assumed to be constant throughout the fill.

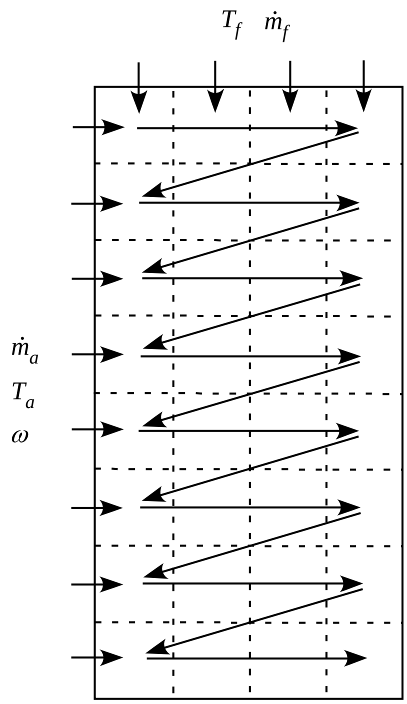


Figure 11. Schematic of a two-dimensional mesh in the fill section of a cross-flow cooling tower. The arrows designate the computational marching scheme.

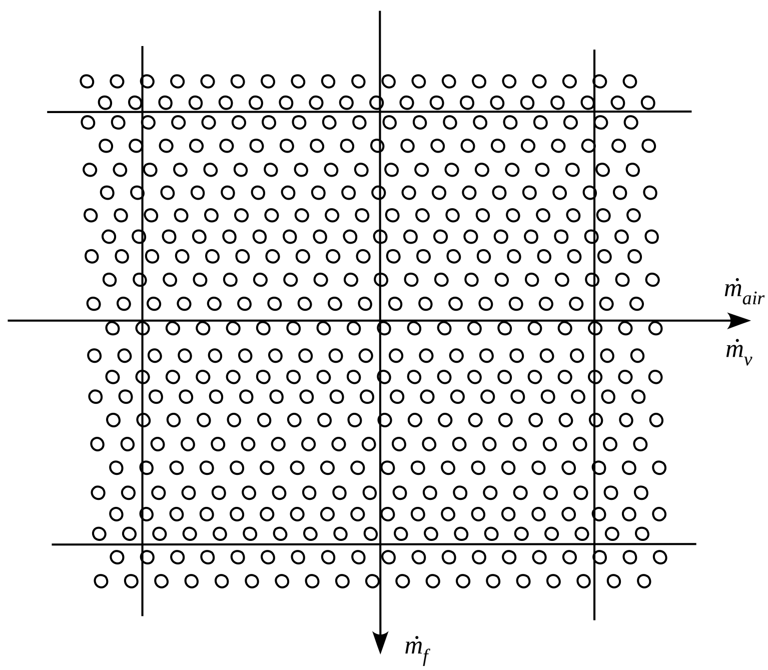


Figure 12. Schematic of the flow in a single control volume of the fill section computational mesh.

During the outer computational loop the mass flowrate of water, water temperature, air temperature and humidity ratio are calculated for each control volume. The evaporation rate from the water droplets for unsaturated and supersaturated air is shown in Eq. 2-9a and 2-9b, respectively. Equation 2-10 is the liquid continuity equation for the water droplets. Equation 2-11 is the air/water vapor energy balance equation. Equation 2-12 is the liquid energy balance equation for the water droplets. Equation 2-13 is the water vapor continuity equation. These equations and their variables are discussed in Appendix B.

$$\dot{m}_{ev_{i,j}} = \frac{\rho_d V k_m A_s M_{H_2O}}{\overline{R}}\left(\frac{P_{vs_{i,j}}}{T_{w_{i,j}}} - \frac{\omega_{i,j} P}{T_{a_{i,j}}(0.622+\omega_{i,j})}\right) \quad (2\text{-}9a)$$

$$\dot{m}_{ev_{i,j}} = \frac{\rho_d V k_m A_s M_{H_2O}}{\overline{R}}\left(\frac{P_{vs_{i,j}}}{T_{w_{i,j}}} - \frac{\omega_{s_{i,j}} P}{T_{a_{i,j}}(0.622+\omega_{s_{i,j}})}\right) \quad (2\text{-}9b)$$

$$\dot{m}_{w\,i,j-1} - \dot{m}_{ev_{ij}} = \dot{m}_{w\,i,j} \quad (2\text{-}10)$$

$$\begin{aligned}\dot{m}_a (C_{p,a_{i,j}}(T_{a_{i-1,j}} - T_{a_{i,j}}) + \omega_{i-1,j} h_{g,a_{i-1,j}} - \omega_{i,j} h_{g,a_{i,j}}) + (\dot{m}_{w_{i,j-1}} - \dot{m}_{w_{i,j}}) h_{g,w_{i,j}} \\ = hA(T_{a_{i,j}} - T_{w_{i,j}})\end{aligned} \quad (2\text{-}11)$$

$$\dot{m}_{w\,i,j-1} h_{f,w_{i,j-1}} - \dot{m}_{w\,i,j} h_{f,w_{i,j}} - (\dot{m}_{w_{i,j-1}} - \dot{m}_{w_{i,j}}) h_{g,w_{i,j}} = hA(T_{w_{i,j}} - T_{a_{i,j}}) \quad (2\text{-}12)$$

$$\dot{m}_a (\omega_{i,j} - \omega_{i-1,j}) = \dot{m}_{w\,i,j-1} - \dot{m}_{w\,i,j} \quad (2\text{-}13)$$

The water droplets in the fill sections of a cross-flow cooling tower and the rain section (not modeled) of a counterflow cooling tower are assumed to be spherical. Equation 2-14 and 2-15 is the Nusselt and Sherwood numbers respectively for flow over a sphere.

$$Nu_d = 2 + \left(0.4 Re_d^{1/2} + 0.06 Re_d^{2/3}\right) Pr^{0.4} \quad (2\text{-}14)$$

$$Sh_d = 2 + \left(0.4 Re_d^{1/2} + 0.06 Re_d^{2/3}\right) Sc^{0.4} \quad (2\text{-}15)$$

The air temperature and humidity ratio will vary along the right-hand vertical side of the fill as shown in Fig. 11. Equation 2-16 and 2-17 is the expression for the mixed mean air temperature and humidity ratio, respectively. The water mass flowrate and temperature will vary along the bottom face of the fill. Equation 2-18 and 2-19 is the expression for the mixed mean mass flowrate of water and temperature, respectively.

$$\overline{T}_a = \frac{\dfrac{\dot{m}_{a_1} \sum_{2}^{nxfvf} T_{a_1}(nxfhf, j) + \dot{m}_{a_2} \sum_{2}^{nxfvf} T_{a_2}(nxfhf, j)}{nxfvc}}{\dot{m}_{a_1} + \dot{m}_{a_2}} \quad (2\text{-}16)$$

$$\overline{\omega} = \frac{\dfrac{\dot{m}_{a_1} \sum_{2}^{nxfvf} \omega_1(nxfhf, j) + \dot{m}_{a_2} \sum_{2}^{nxfvf} \omega_2(nxfhf, j)}{nxfvc}}{\dot{m}_{a_1} + \dot{m}_{a_2}} \quad (2\text{-}17)$$

nxfhf ....number of cross-flow fill horizontal faces
nxfvf ....number of cross-flow fill vertical faces
nxfvc ....number of cross-flow fill vertical cells

$$\overline{\dot{m}}_w = \sum_{2}^{nxfhf} \dot{m}_{w_1}(i, nxfvf) + \sum_{2}^{nxfhf} \dot{m}_{w_2}(i, nxfvf) \tag{2-18}$$

$$\overline{T}_w = \frac{\dfrac{\sum_{2}^{nxfhf} \dot{m}_{w_1}(i, nxfvf) \sum_{2}^{nxfhf} T_{w_1}(i, nxfvf) + \sum_{2}^{nxfhf} \dot{m}_{w_2}(i, nxfvf) \sum_{2}^{nxfhf} T_{w_2}(i, nxfvf)}{nxfhc}}{\sum_{2}^{nxfhf} \dot{m}_{w_1}(i, nxfvf) + \sum_{2}^{nxfhf} \dot{m}_{w_2}(i, nxfvf)} \tag{2-19}$$

nxfhc ....number of cross-flow fill horizontal cells

With the fan shut-off, air will flow through the cooling tower due to buoyancy and wind pressure in the center region. Figure 13 is a schematic of natural draft/wind-aided flow through a cross-flow cooling tower. Wind will stagnate on the windward side of the cooling tower, increasing the pressure on the vertical face. Because air enters the cooling tower through almost the entire vertical face, natural draft flow through cross-flow cooling towers is sensitive to wind. Equation 2-20 shows the mechanical energy equation for the flows through the two sides of the cooling tower. p_1 is the pressure on the windward side of the cooling tower, and p_2 is the pressure on the leeward side, assumed to be atmospheric. The stagnation pressure is calculated from the component of wind velocity normal to the windward side of the cooling tower. The effect of wind is to increase flow through the windward side of the cooling tower and decrease flow through the leeward side.

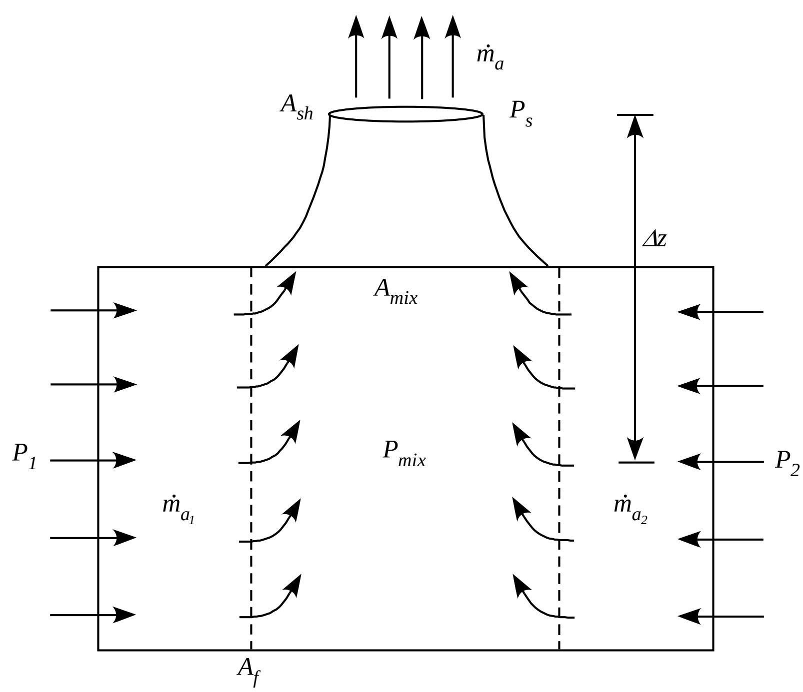


Figure 13. Schematic of natural draft/wind-aided flow through a cross-flow cooling tower.

$$\dot{m}_{a_1} = \frac{\dot{m}_a}{2} + \frac{\rho A_f^2}{(1+K_f)\dot{m}_a}(p_1 - p_2)$$
$$\dot{m}_{a_2} = \frac{\dot{m}_a}{2} - \frac{\rho A_f^2}{(1+K_f)\dot{m}_a}(p_1 - p_2) \qquad (2\text{-}20)$$

Equation 2-21 is the overall mechanical energy equation for natural draft/wind-aided flow through the cooling tower. This fourth-order equation is solved iteratively, by Newton's method, for the total mass flowrate of dry air. The equation and the solution technique are discussed in Appendix D.

$$f = \left[\frac{1+K_{sh}}{2\rho A_{sh}^2} + \frac{1+K_f}{8\rho A_f^2} - \frac{1}{2\rho A_{mix}^2}\right]\dot{m}_a^4 - \left[\frac{p_1 - p_2}{2} + (\rho - \rho_{mix})g\Delta z\right]\dot{m}_a^2 + \frac{\rho A_f^2}{2(1+K_f)}(p_1 - p_2)^2 \qquad (2\text{-}21)$$

If the pressure difference between the two sides is large enough, the flowrate through the leeward side of the cooling tower, from Eq. 2-20, will be negative. The numerical scheme for evaluating flow through the fill section is not valid for negative flowrates, therefore when the predicted flowrate through the leeward side of the cooling tower is negative; the flowrate is set to be zero. If flow through one side of the cooling tower is stagnated, the overall mechanical energy equation for the cooling tower changes. Figure 14 is a schematic of a cross-flow cooling tower with flow only through the windward side. Equation 2-22 is the mechanical energy equation for natural draft/wind-aidied flow through the windward side of the cooling tower. This quadratic equation is solved iteratively, by Newton's method, for the total mass flowrate of dry air.

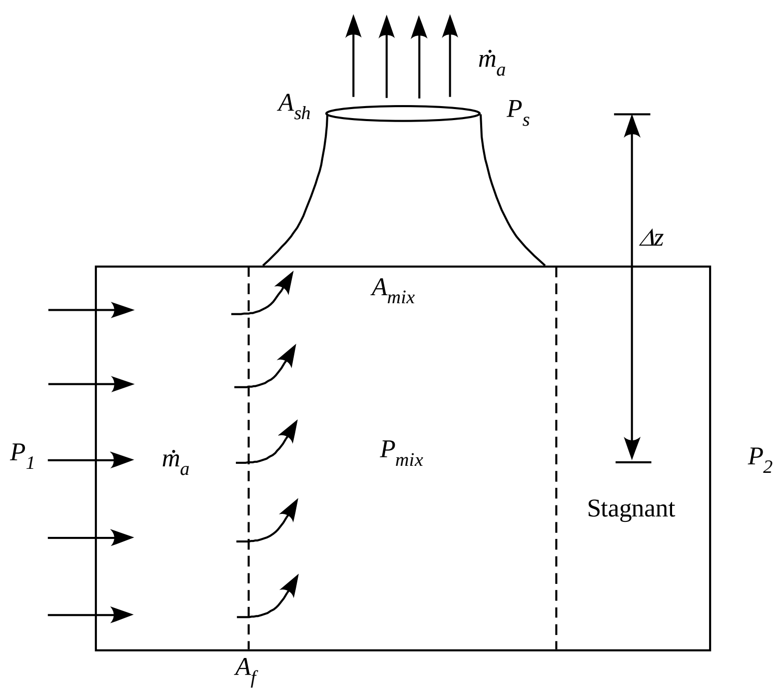


Figure 14. Schematic of natural draft/wind-aided flow through a cross-flow cooling tower with stagnated flow in the leeward side

$$f = \left[\frac{1+K_{sh}}{2\rho A_{sh}^2} + \frac{1+K_f}{2\rho A_f^2} + \frac{1}{2\rho A_{mix}^2} \right] \dot{m}_a^2 - \left[(p_1 - p_{atm}) + (\rho - \rho_{mix}) g \Delta z \right] \tag{2-22}$$

2.1.2 Outer Model

Using specified geometry and input parameters, CTTool iterates on the inlet water temperature to the cooling tower(s) until the sensor temperature matches the target temperature of interest.

The targeted temperature includes the air exhaust (throat) temperature for a single cooling tower or an area-weighted temperature comprised of the air exhaust temperature, shroud temperatures and decking temperature of a single or multiple cooling towers.

2.1.2.1 Rochester Institute of Technology Sensor LUT Temperature Correction Factors

A 3-D radiation heat transfer model of a MDCT is modeled in DIRSIG. The parameters varied within the DIRSIG simulation are MDCT internal temperature (throat), MDCT external temperature, fan emissivity, effective sky temperature and sensor zenith angle.

The MODTRAN simulation provides spectral atmospheric transmission and spectral atmospheric path radiance curves for the same spectral range as the DIRSIG simulation. The parameters that are varied include the ambient air temperature, ambient dew point temperature and water vapor plume length.

The sensor model in DIRSIG computes the apparent temperature of each pixel within the mixed or cavity ROI inside the cooling tower throat. The mixed ROI includes the fan blades and internal throat cavity.

DIRSIG and MODTRAN simulations are executed for a series of 32,400 parameter value combinations, from those mentioned above. The resulting temperature errors (sensor minus MDCT internal temperature) are organized into a LUT of 32,400 entries that list the temperature error for the mixed and cavity ROI for every combination of target space parameter values

A multiple linear regression of the target space parameters is generated for the mixed and cavity ROI temperature error. These coefficients are read into the CTTool software.

The regression equation for the mixed ROI temperature error is

$$\hat{y}_1 = xmix(0) + \sum_{i=1}^{7} xmix(i)xvec(i) \tag{2-23}$$

Similarly, the regression equation for the cavity ROI temperature error is

$$\hat{y}_2 = xcav(0) + \sum_{i=1}^{7} xcav(i)xvec(i) \tag{2-24}$$

The vector predictor estimates for a given image is

xvec(1) = ...cooling tower external temperature, K

xvec(2) = ...fan blade emissivity
xvec(3) = ...effective sky temperature, K
xvec(4) = ...sensor zenith angle, deg
xvec(5) = ...ambient air temperature, K
xvec(6) = ...ambient dew point temperature, K
xvec(7) = ...plume path length (sensor line-of-sight), m

See (Montanaro, 2009) for details of this methodology.

2.1.2.2 Single Cooling Tower (Throat-only)

The throat-only region-of-interest (ROI) is usefull when the remote sensor is able to resolve the temperature profile within the throat of the cooling tower. A sensor delta-T and two sensor look-up-table (LUT) options are available within the CTTool.

- Sensor delta-T: A radiometer-measured throat temperature with the ambient temperature substracted out.
- Mixed ROI LUT: Compute temperature correction using Eq. 2-23 and the appropriate predictor estimates for the image. This is recommended for fan on operation.
- Cavity ROI LUT: Compute temperature correction using Eq. 2-24 and the appropriate predictor estimates for the image.

The inlet cooling water temperature to the cooling tower is varied until one of the following cost functions is minimized.

$$f = \begin{cases} (T_a - T_{db}) - (T_{app} - T_{db}) \\ (T_{ROI} - T_a) - \hat{y}_1 \\ (T_{ROI} - T_a) - \hat{y}_2 \end{cases} \tag{2-25}$$

T_{app} ....apparent sensor temperature, K
T_{ROI} ....mixed or cavity ROI temperature, K
T_a ....air exhaust temperature, K

2.1.2.2 Single or Multi-cell Cooling Tower (Throat and exposed cooling tower materials)

A remote sensor is not typically able to resolve the temperature profile within the throat of a cooling tower. The limitation of the sensor GSD and the sensor line-of-sight to the cooling tower generates an apparent temperature for the composite throat and exposed cooling tower materials. The area-weighted temperature is computed from the throat and exposed cooling tower material temperatures for each cooling tower in the array. A ray tracing algorithm with the sensor line-of-sight is used to compute area fractions for each component. The area-weight temperature is computed as

$$T_{avg} = \frac{nct\left(pc(1)+pc(2)\right)T_{w_i} + pc(3)\sum_{1}^{nct} T_d(i) + pc(4)\sum_{1}^{nct} T_a(i) + pc(5)\sum_{1}^{nct} T_{is}(i) + pc(6)\sum_{1}^{nct} T_{os}(i)}{nct} \tag{2-26}$$

nct ....number of cooling towers
T_{w_i} ....inlet water temperature, K
$T_d(i)$ ....deck surface temperature for cooling tower i, K
$T_a(i)$ ....exhaust air temperature for cooling tower i, K
$T_{is}(i)$ ....shroud inner surface temperature for cooling tower i, K
$T_{os}(i)$ ....shroud outer surface temperature for cooling tower i, K
pc ....area fractions of each cooling tower component

The inlet cooling water temperature to the single or multi-cell cooling tower is varied until the following cost function is minimized.

$$f = (T_{avg} - T_{db}) - (T_{app} - T_{db}) \rightarrow 0 \tag{2-27}$$

2.1.2.2 Deck Model

The deck model temperature is computed by solving a surface energy budget equation that models the thermal radiation fluxes entering and leaving the deck surface, the solar flux, convective heat transfer, latent heat flux (condensation only) and heat conduction from the air space above the drift eliminators through the deck material to the air:

$$h\rho_d c_{pd} \frac{dT_d}{dt} = F_{lwd} + F_{lwu} + F_{sw} + H_s + H_\ell + \alpha\left(T_{avg} - T_d\right) \tag{2-28}$$

h ....deck thickness, m
ρ_d ....density of deck material, kg/m^3
c_{pd} ....specific heat of the deck material, J/kg K
T_d ....deck surface temperature, K
F_{lwd} ....downward-directed thermal radiation (sky radiation), W/m^2
F_{lwu} ....upwelling thermal radiation or deck self-emmitted radiance, W/m^2
F_{sw} ....short-wave radiation or solar flux at the ground, W/m^2
H_s ....sensible heat flux, W/m^2
H_ℓ ....latent (condensation) heat flux, W/m^2
α ....effective thermal conductance across deck thickness, W/m^2 K
T_{avg} ....average of deck and exhaust air temperatures, K

The terms H_ℓ, and H_s were modeled with standard atmospheric boundary layer heat and mass transfer functions[2]. The term F_{lwd} was modeled by simple empirical relationships presented in Reference 3 (a more elaborate thermal radiation transfer model could not be used because it would have increased code execution time too much.)

Equation 2-28 is solved by assuming that the deck surface temperature is slowly varying late at night (typical imaging time), so the time derivative can be neglected, which leaves a fourth-order polynomial that is solved numerically using Newton's method. The latent heat term H_ℓ is evaluated only when the deck surface saturation water vapor pressure is less than the ambient water vapor pressure, which implies condensation (dew) or sublimation (frost) formation on the deck surface is occurring. This is the likely situation late at night. Evaporation of dew or sublimation of frost will usually occur in the morning as the sun heats the deck surface, which is not a typical imaging time. This approximation eliminates the necessity of keeping track of a surface water/ice mass budget in the model. If the surface saturation water vapor pressure is greater than the ambient water vapor pressure, then H_ℓ is set equal to zero.

It is assumed that the deck material has a thermal emissivity close enough to water (0.96), that no correction is needed for the remote-sensing based temperature retrieval, which uses an emissivity of 0.96 to convert radiance to temperature. Northrop-Grumman made emissivity measurements of the SRS F-Area and A-Area cooling tower decks and found that the combined plastic and metal F-Area deck had an emissivity of 0.98 and the wooden A-Area deck had an emissivity of 0.95; so the assumption appears to be justified.

The shroud inner and outer temperatures are computed using Eq. 2-29 and 2-30, respectively.

$$\frac{k_s}{\delta_s}\left(T_{os} - T_{is}\right) = h_{is}\left(T_{is} - T_a\right) \tag{2-29}$$

$$\frac{k_s}{\delta_s}\left(T_{os} - T_{is}\right) = 0.5\varepsilon_s\sigma\left(T_{eff}^4 + \varepsilon_g T_{db}^4\right) - \varepsilon_s\sigma T_{os}^4 - h_{os}\left(T_{is} - T_a\right) \tag{2-30}$$

k_s ....shroud thermal conductivity, W/m K
δ_s ....thickness of shroud, m
h_{is} ....heat transfer coefficient for the inner surface of the shroud, W/m^2 K
h_{is} ....heat transfer coefficient for the outer surface of the shroud, W/m^2 K
T_{is} ....inner surface temperature of the shroud, K
T_{os} ....outer surface temperature of the shroud, K
T_{eff} ....effective temperature of the mixture of land surface and sky (T_{db} – 10), K
T_{db} ....dry-bulb temperature, K
ε_s ....shroud emmissivity, W/m K
σ ....Stefan-Boltzmann constant, W/m^2 K^4

T_{eff} is the effective temperature of the mixture of land surface and sky that the shroud will receive thermal radiation from (as a vertical surface). Based on field measurements, T_{eff} is assumed to be the ambient air temperature minus 10ºC. Evaporation and condensation of water vapor on the outer surface of the shroud are not included in the shroud surface energy budget. The inner and outer surface temperatures of the shroud are solved using Newton's method.

The remote thermal imaging system will usually view the cooling tower at a zenith angle greater than zero, so the side of the shroud will block some of the throat from view. If the entire deck area is used in the temperature retrieval, then the relative areas of the throat, shroud and deck must be computed as a function of the sensor zenith and azimuth angles to determine what contributions these different surfaces had on the retrieved temperature.

Figure 15 is a schematic of a side view of the cooling tower which approximates the shroud as a vertical cylinder. A sensor looking at the tower from some zenith angle Z will have some part of the throat area blocked by the shroud. Part of the deck will also be blocked by the shroud. Figure 15 shows the relationships between the deck and shroud dimensions and zenith angle and the total area blocked by the shroud.

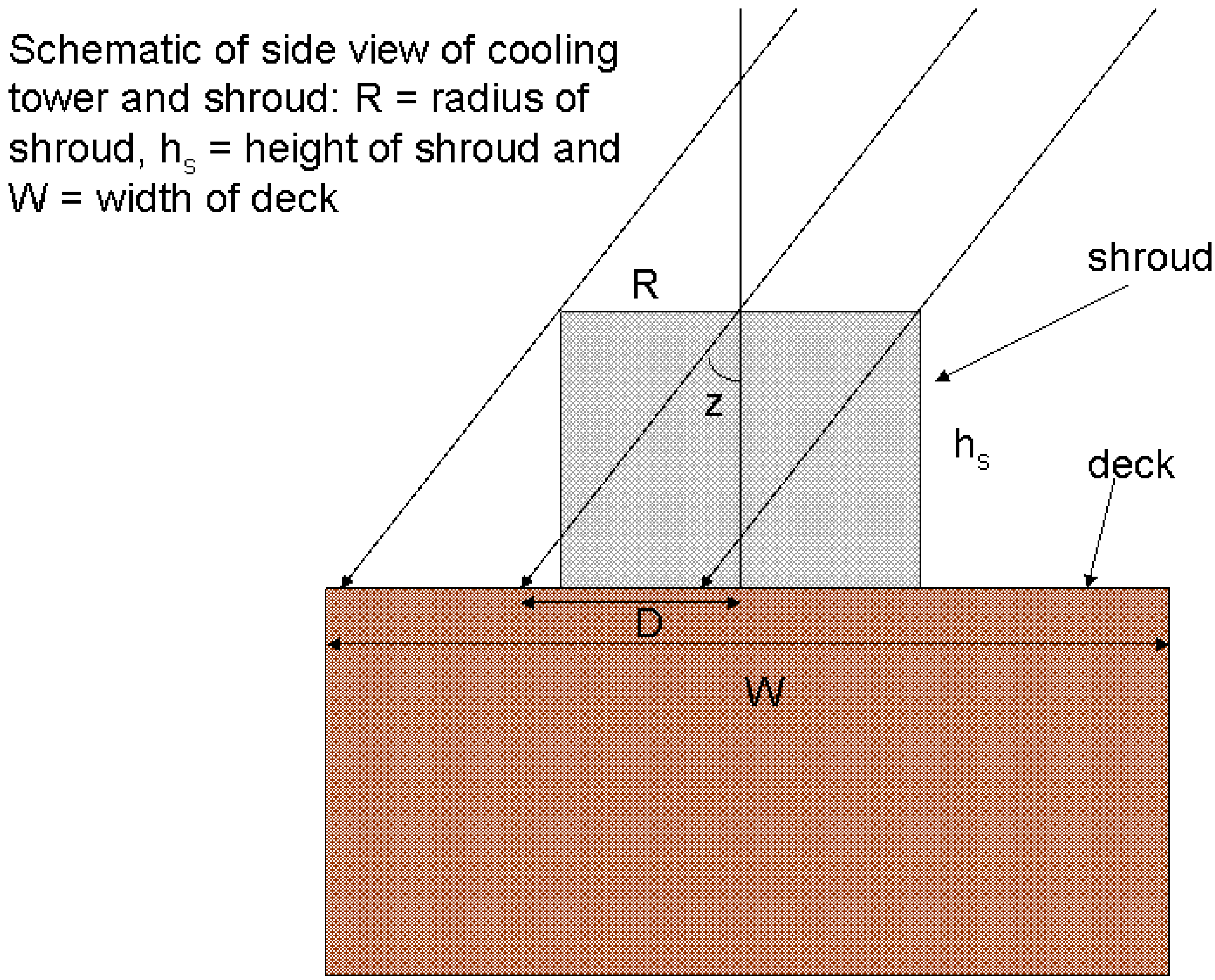


Figure 15. Schematic of side view of cooling tower, which shows relationships between parameters needed to calculate area blocked from sensor view by shroud.

Some cooling towers have areas of the deck over which heated water is pumped, which subsequently spreads and falls through grids of small holes to honeycomb-like plastic fill material or splash plates, which are designed to increase heat and mass transfer from the water to the air. These structures are called water decks, and should lead to more accurate estimates of Q when they are present, because they directly expose the heated water entering the cooling tower to the remote sensing system. Figure 16 is a photograph of one side of a cooling tower deck that contains a water deck. Water decks are typically on both side of the cooling tower fan, to ensure uniform distribution of water to the fill or splash plates. In practice, water decks often produce flow maldistribution because the wooden water decks warp and crack.

Figure 16. Photograph of cooling tower water deck, which parallels the long axis of the tower. Water decks typically are placed on both side of the tower.

The water deck represents another type of deck surface which must be accounted for when determining what the shroud is blocking from view of the remote sensor. The cooling tower model uses a ray-tracing calculation to determine the different deck areas exposed to the sensor. A sample calculation from the ray tracing subroutine is shown in Figure 17. Note that there are six areas that are included in the ray-tracing simulation: 2 water decks (1, 2), the solid deck (3), the part of the throat exposed to the sensor (4), the deck hidden by the shroud (5) and the throat area hidden by the shroud (6). The ray-tracing subroutine computes the amount of each of the six areas that was visible to the sensor for each image as a function of sensor zenith and azimuthal angles, and the dimensions of the cooling tower. The inside of the shroud is computed from Eq. 2-29. The outer shroud temperature is computed from Eq. 2-30.

The cooling tower model uses the relative proportions of each of the six areas to the total deck area to compute an area-weighted deck temperature for comparison to the sensor temperature measurement. At zenith angles greater than a value that depends on shroud height and diameter, none of the throat will be visible (typically a zenith angle of about 45º). If there is no water deck, then only the shroud and solid deck will be used in the temperature calculation. The uncertainties in the material properties of the solid deck and the shroud imply that the uncertainty of a Q calculation based only on these deck components will be much greater than a throat-only calculation or a calculation in which both the throat and water decks are observed by the sensor.

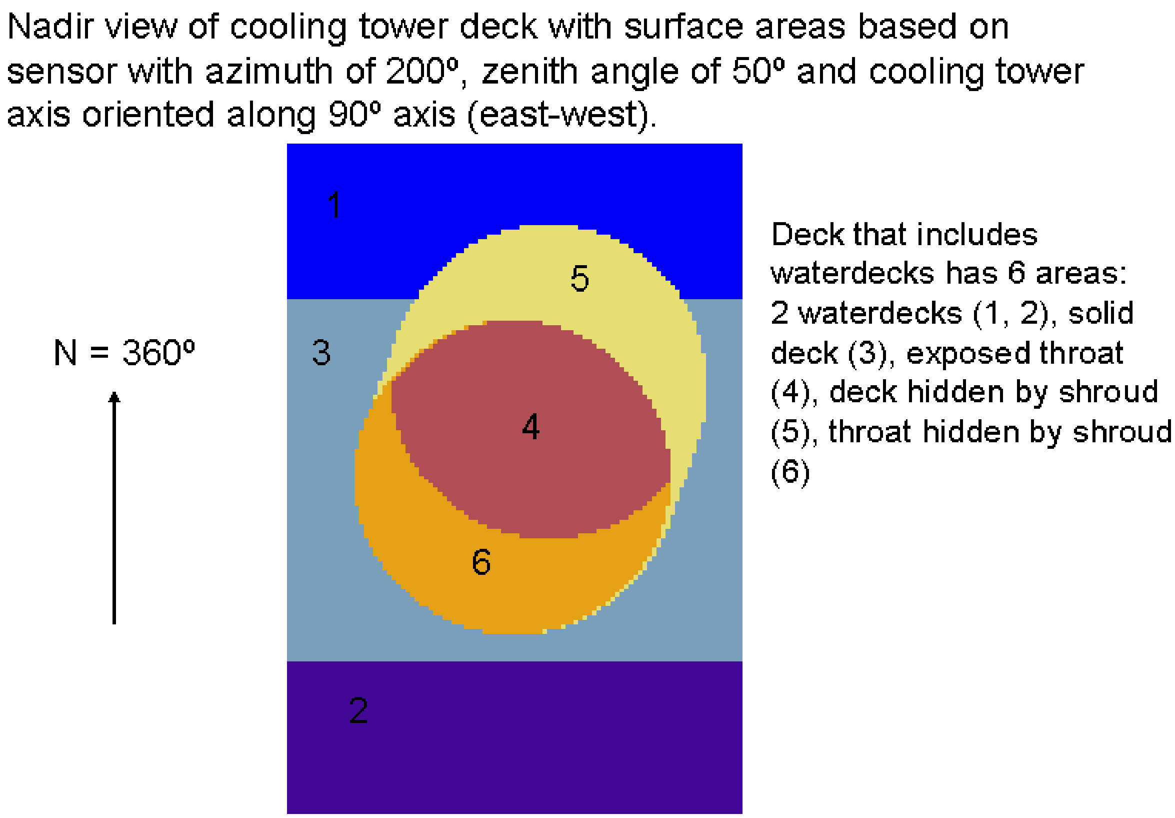


Figure 17. Schematic derived from output of ray-tracing subroutine.

One additional feature of the deck temperature calculation is the partitioning of the downwelling radiation between the sky and the sides of the shroud, which will block at least some of the sky from all locations on the deck. Ray-tracing calculations were performed for the SRS F and H Area cooling towers. Both calculations found that about 17% of the sky would be blocked by the shroud (averaged over entire deck). Since cooling towers always have railings, lights and other objects on the deck, the total blockage has been set equal to 20% in this code. Figure 18 is an image created from this ray-tracing calculation, showing the greater amount of sky blockage by the shroud at deck locations immediately adjacent to the shroud (nearly 50%). The percentages are somewhat higher between adjacent shrouds, and lowest at the edges of the deck.

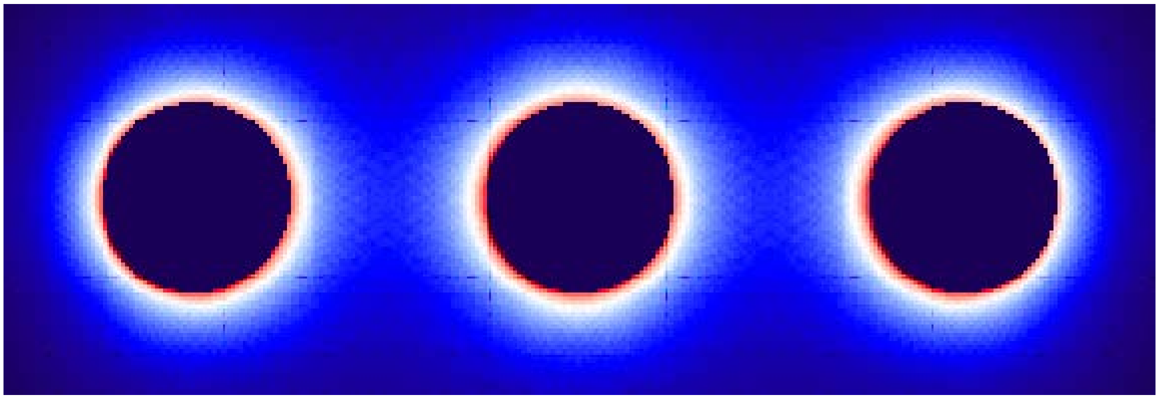


Figure 18. Image showing computed sky blockage by shrouds in multi-cell deck. White areas have highest percentage of sky blockage.

3.0 Tool Description

3.1 Data structure

The input and output files associated with the CTTool code and their contents are described below.

3.2 Super file

The CTTool super file is a special type of file used to organize the individual files for input and output operations. The super file is a text file that contains the names of input/output files. The super file is read from the command line (UNIT=5). The first line of the super file is an identifier card, “CTToolSup”. After the identifier line, each subsequent line is preceded by a four-letter category code and a filename. The category code and filename have to be enclosed in single or double quotes. The MINP, SMRS, CFCT or XFCT categories are required. The other categories are specified based on the state of the simulation and output options. Table 3-1 shows the format of a typical super file.

Table 3-1. CTTool Super File Format

Category	File Name
CTToolSup	
‘MINP’	‘SRNL20Jun05G09.minp’
'SMRS'	‘SRNL20Jun05G09.smrs’
'CFCT'	‘SRNL20Jun05G09.cfct’
'LUTB'	‘SRNL20Jun05G09.lutb’
'MOUT'	‘SRNL20Jun05G09.mout’
'DIAG'	‘SRNL20Jun05G09.diag’

3.3 File content and organization

Table 3-2 summarizes the input and output (I/O) files specified within the CTTool super file. The detailed content and organization of each file is presented in Appendix A.

CTTool uses list-directed **READ** statements to process numeric data in the model input, surface meteorology and remote sensing data, counterflow cooling tower parameters, cross-flow cooling tower parameters, sensor Look-Up Table and cooling tower benchmarking data. Therefore, there are no data formatting requirements and the data associated with a given **READ** statement may occupy multiple lines in the input files. Data groups are delineated by required comment lines that serve the purpose of annotating the input.

Besides a main output file and optional diagnostic file, CTTool can create an additional output files intended for Tecplot™ post-processing.

Table 3-2. Summary of CTTool Input and Output Files

File	Unit	I/O	Category
super file	5	input	
model input	10	input	MINP
surface meteorology and remote sensing data	11	input	SMRS
counterflow cooling tower parameters	12	input	CFCT
cross-flow cooling tower parameters	13	input	XFCT
sensor Look-Up Table	14	input	LUTB
F, H or A-Area cooling tower benchmarking data	97	input	BMRK (roi= -2 to -4)
model output	20	output	MOUT
diagnostic output	21	output	DIAG
CTModelTemps.plt	2	output	DIAG (roi=1)
imgxxx.out	3	output	DIAG (roi=1)
matid0.plt	3	output	DIAG (roi=1)
matid.plt	3	output	DIAG (roi=1)
raytracing.txt	4	output	DIAG (roi=1)
Water-side.plt	90	output	CFCT, DIAG
Air-side.plt	91	output	CFCT, DIAG
Le-side.plt	92	output	CFCT, DIAG
Water-side-1.plt	90	output	XFCT, DIAG
Air-side-1.plt	91	output	XFCT, DIAG
Le-side-1.plt	92	output	XFCT, DIAG
Water-side-2.plt	93	output	XFCT, DIAG
Air-side-2.plt	94	output	XFCT, DIAG
Le-side-2.plt	95	output	XFCT, DIAG

File	Unit	I/O	Category
F, H or A-Area cooling tower water temperatures	98	output	H2OT (roi= -2 to -4)
F, H or A-Area cooling tower air temperatures	99	output	AIRT (roi= -2 to -4)

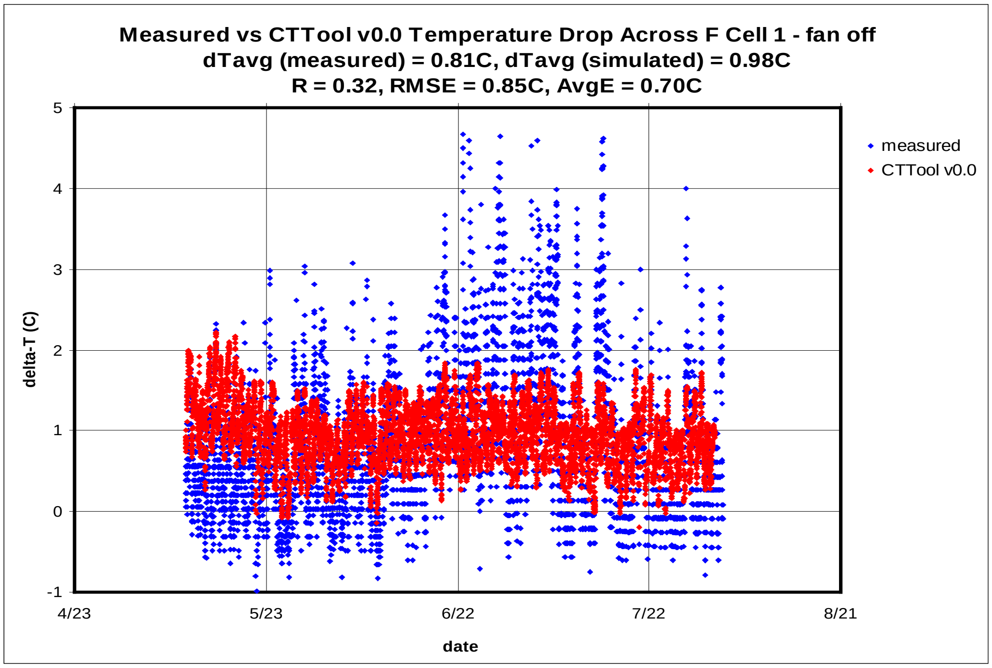
4.0 Engineering Validation

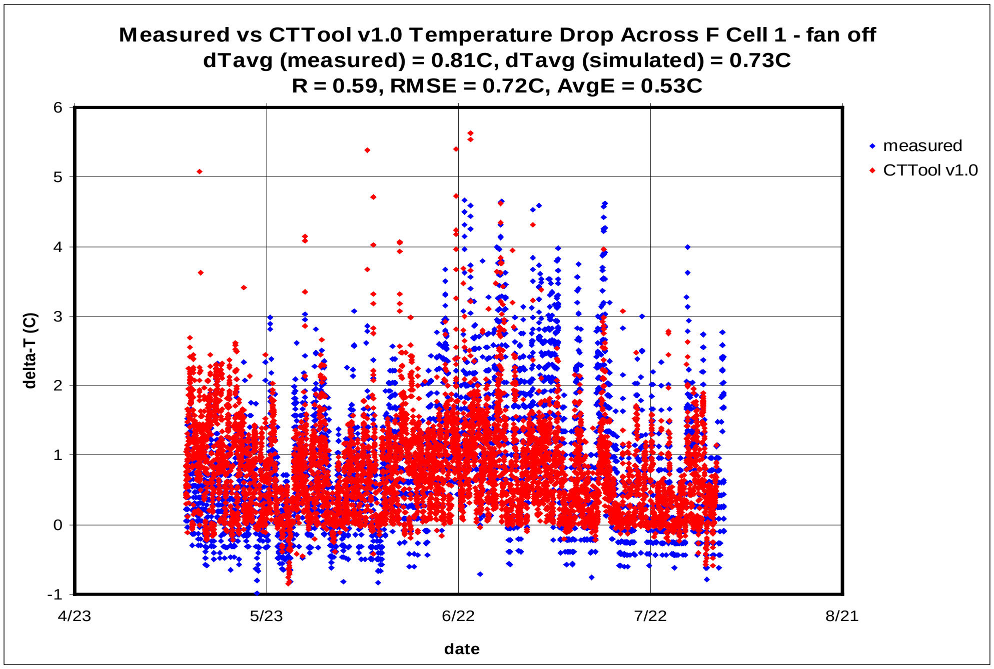
SRNL's sponsors have funded data collections in and around 3 multi-cell cooling towers at the Savannah River Site: F-Area, H-Area and A-Area. The databases created from the these collections were used to benchmark the MDCT models in this DOE-funded project The data collections included MDCT operation with fan on and fan off.

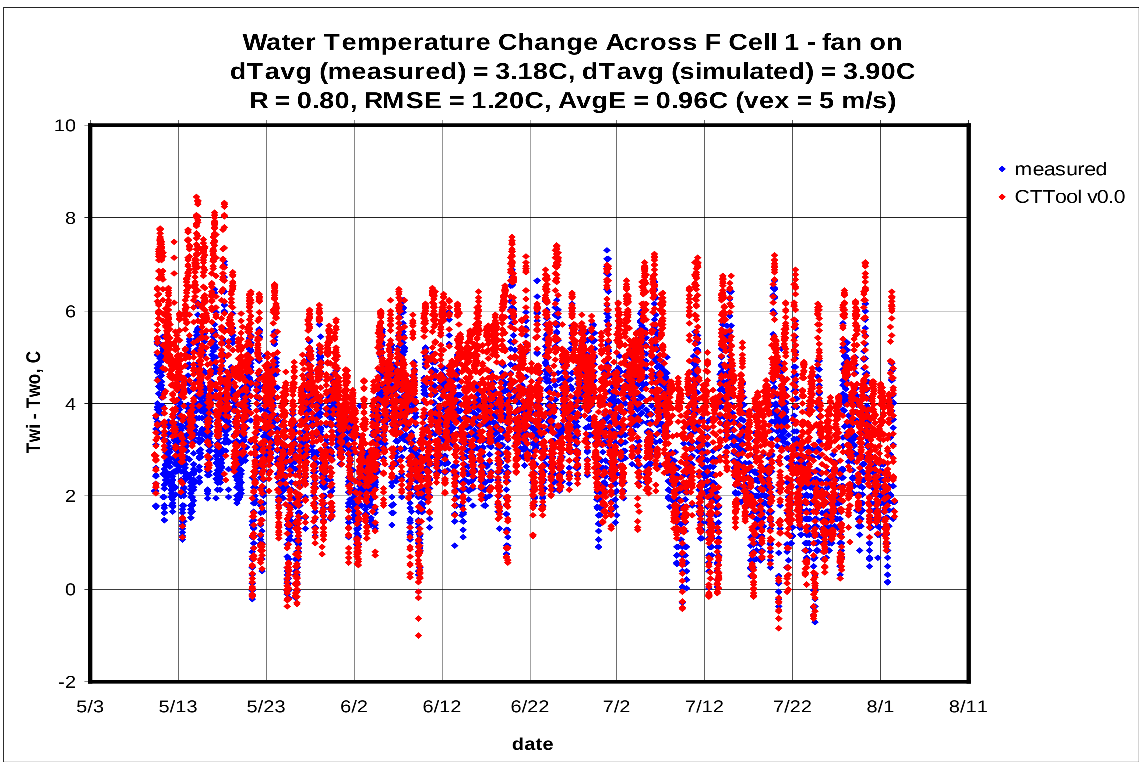
In the plots that follow below, CTTool v0.0 and v1.0 refer to the previous and new version of the Cooling Tower Exploitation Tool, respectively. The average measured and simulated cooling water temperature change dTavg, correlation coefficient R, root-mean-square error RMSE and average error AvgE are computed for each dataset.

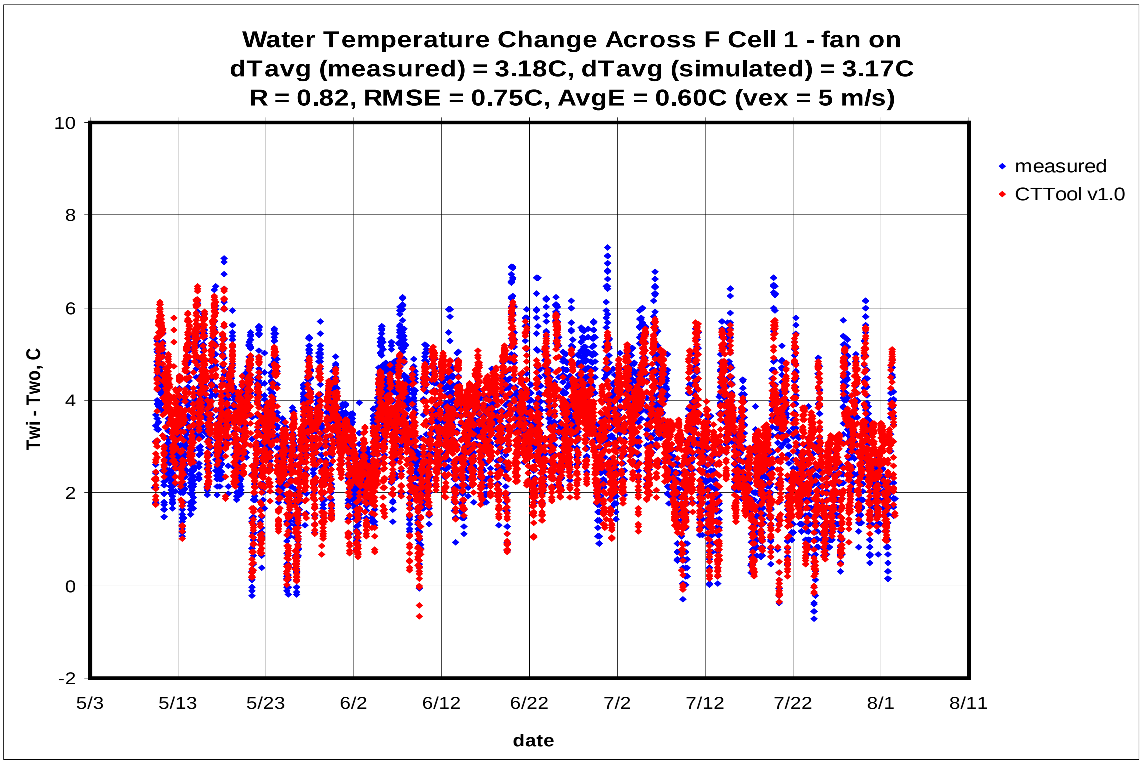
A model-to-model comparison is shown in section 4.4.

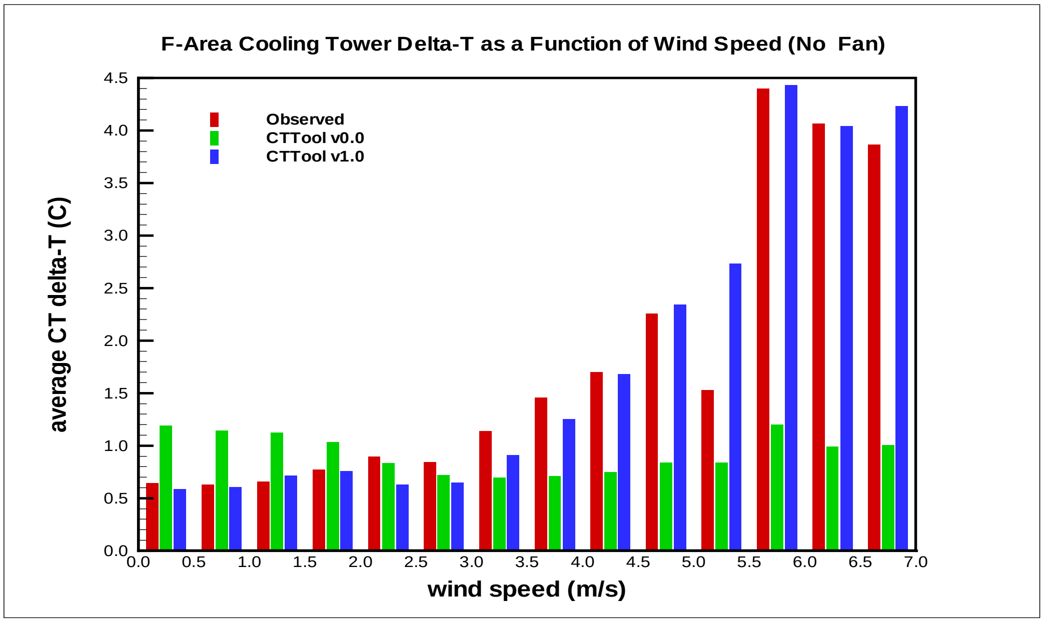
4.1 F-Area Cooling Tower Benchmarking

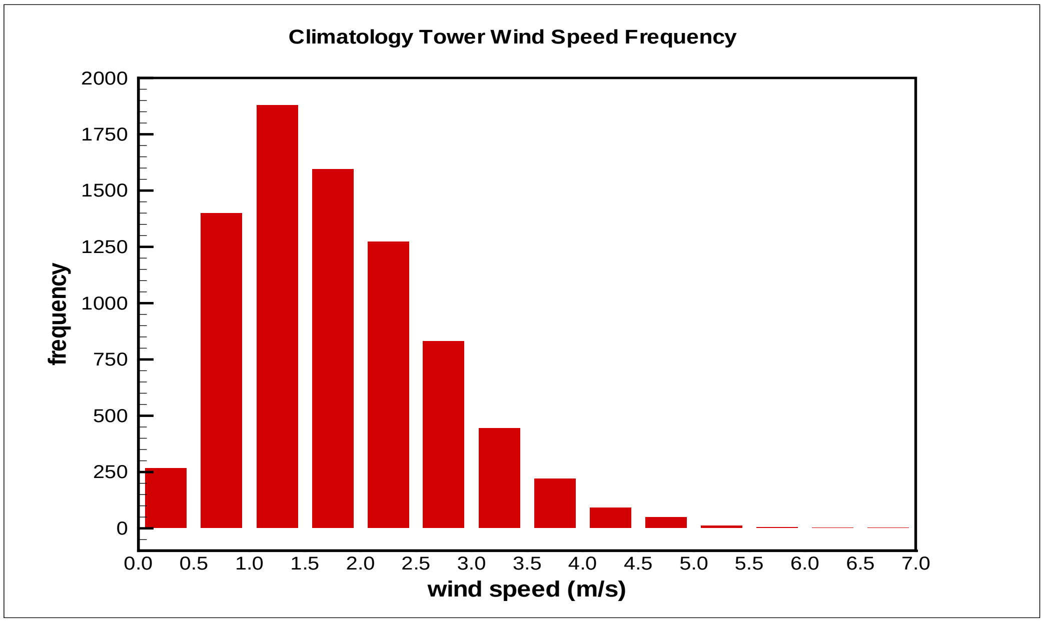



Measured vs CTTool v1.0 Temperature Drop Across F Cell 1 - fan off
dTavg (measured) = 0.81C, dTavg (simulated) = 0.73C
R = 0.59, RMSE = 0.72C, AvgE = 0.53C
delta-T (C)
date
measured
CTTool v1.0
6
5
4
3
2
1
0
-1
4/23
5/23
6/22
7/22
8/21


Water Temperature Change Across F Cell 1 - fan on
dTavg (measured) = 3.18C, dTavg (simulated) = 3.90C
R = 0.80, RMSE = 1.20C, AvgE = 0.96C (vex = 5 m/s)
Twi - Two, C
date
measured
CTTool v0.0
10
8
6
4
2
0
-2
5/3
5/13
5/23
6/2
6/12
6/22
7/2
7/12
7/22
8/1
8/11

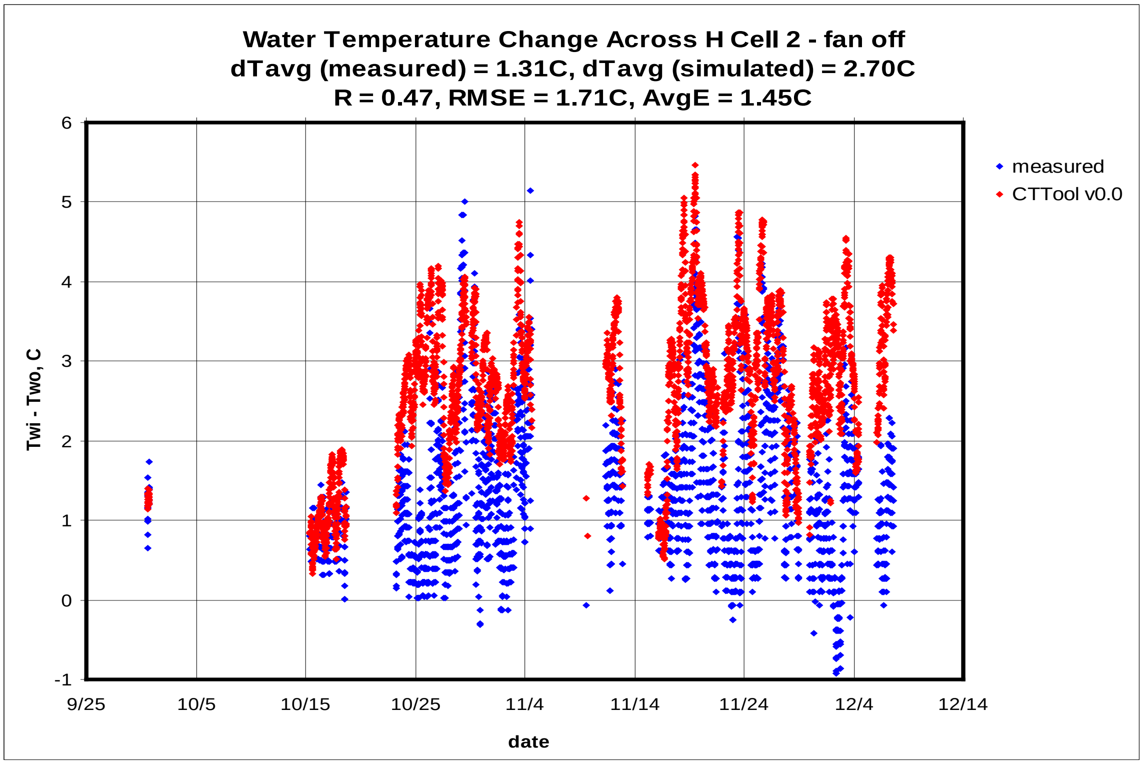

Water Temperature Change Across F Cell 1 - fan on
dTavg (measured) = 3.18C, dTavg (simulated) = 3.17C
R = 0.82, RMSE = 0.75C, AvgE = 0.60C (vex = 5 m/s)
Twi - Two, C
date
measured
CTTool v1.0
10
8
6
4
2
0
-2
5/3
5/13
5/23
6/2
6/12
6/22
7/2
7/12
7/22
8/1
8/11

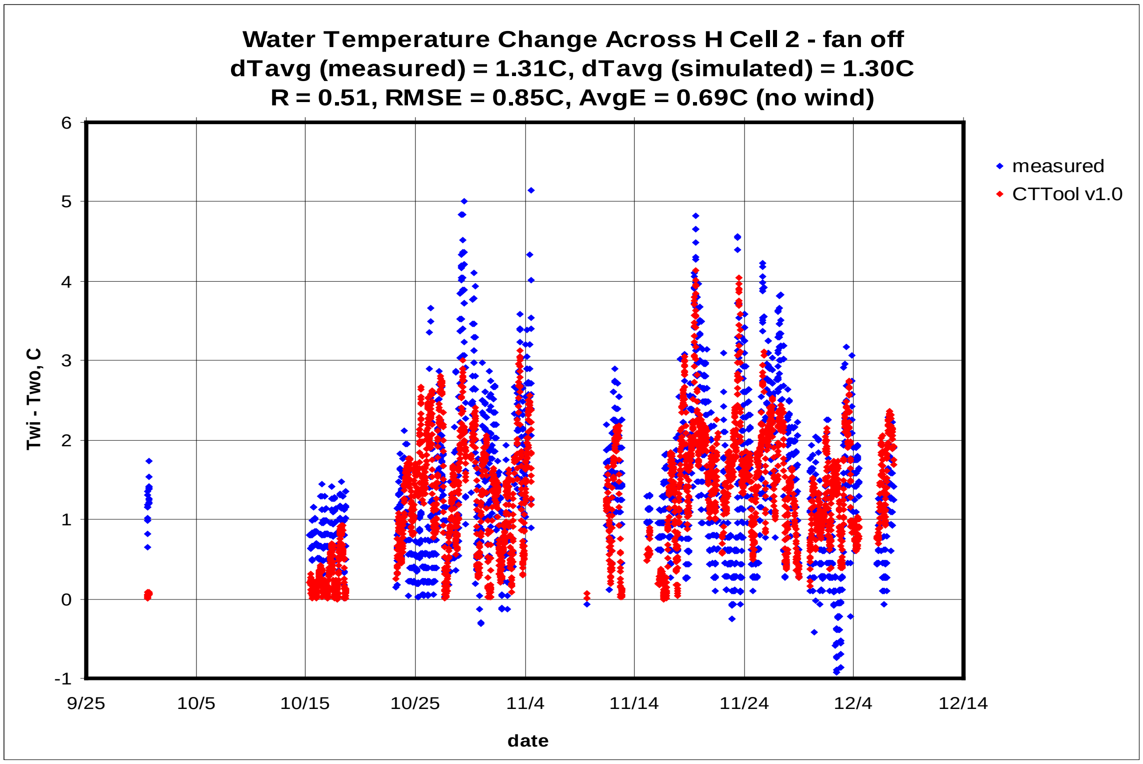

F-Area Cooling Tower Delta-T as a Function of Wind Speed (No Fan)
average CT delta-T (C)
wind speed (m/s)
Observed
CTTool v0.0
CTTool v1.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0

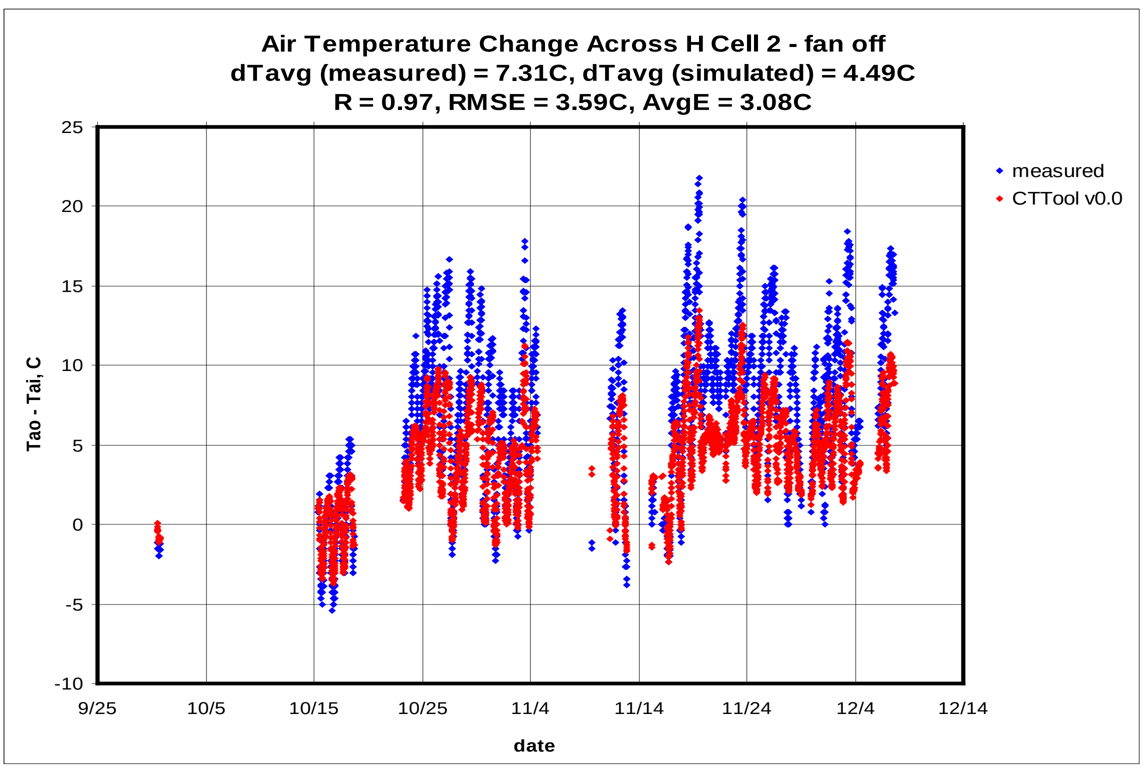


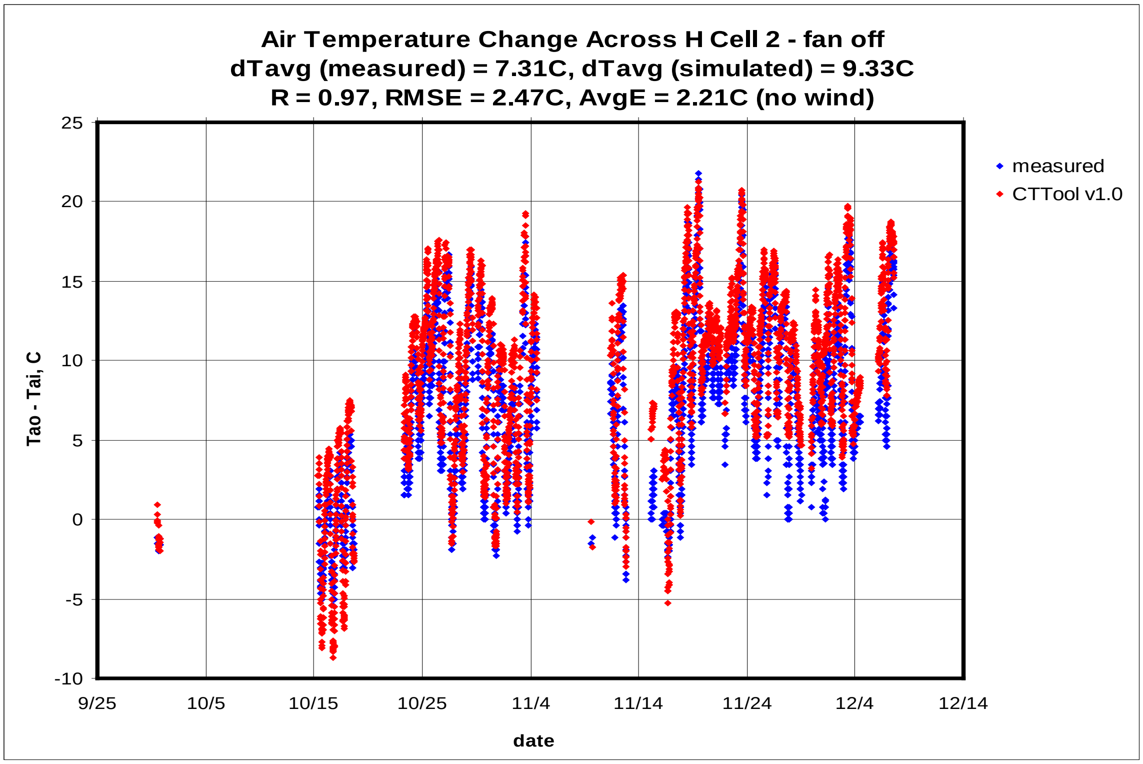
4.2 H-Area Cooling Tower Benchmarking

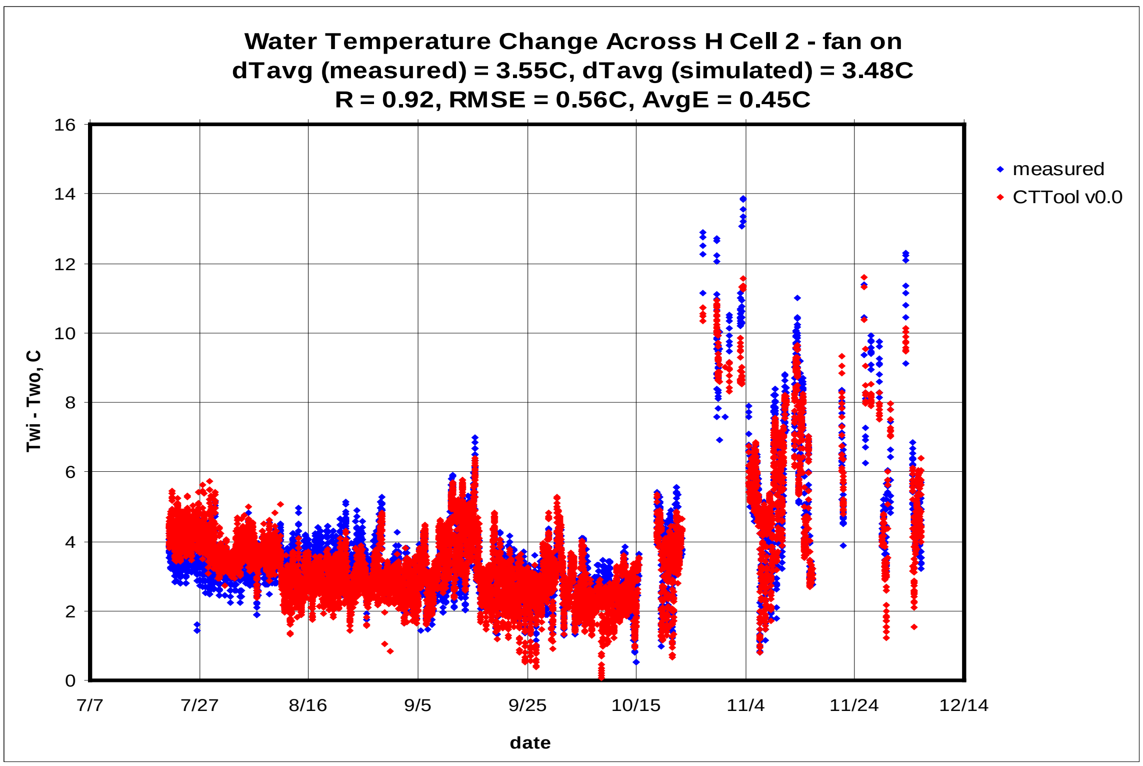
Water and air temperature changes across the cooling towers are presented for H Cell 2 for fan off and fan on operation.

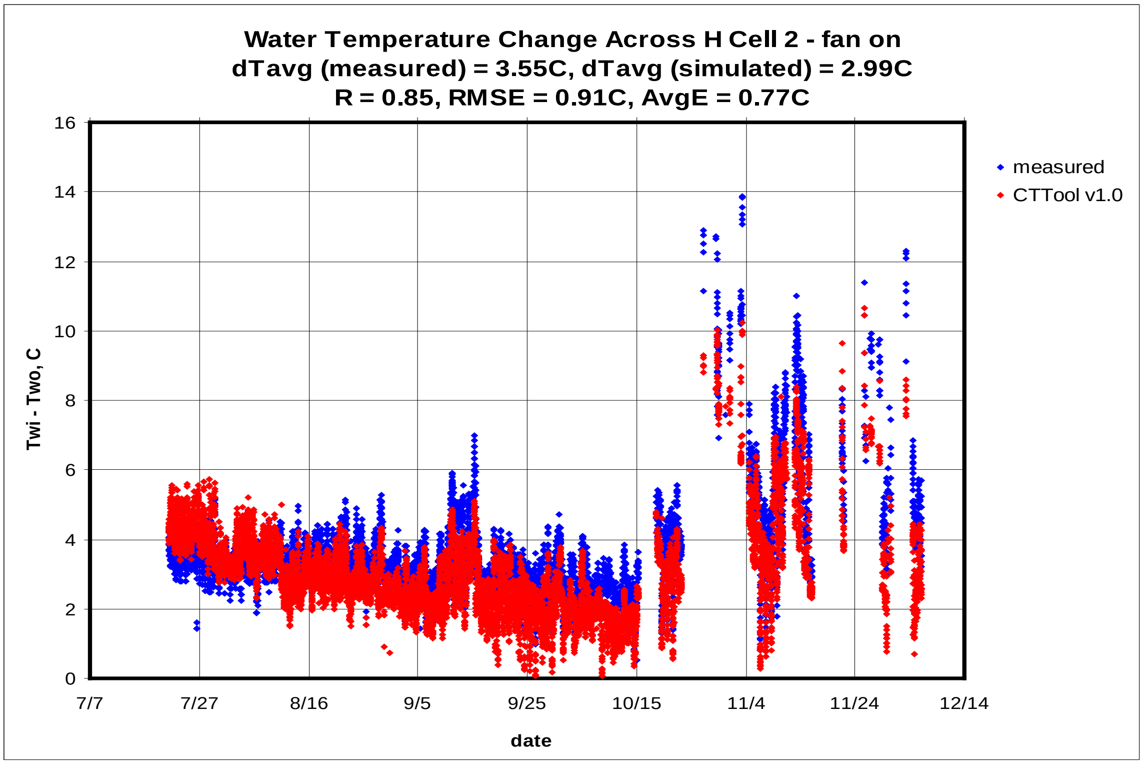


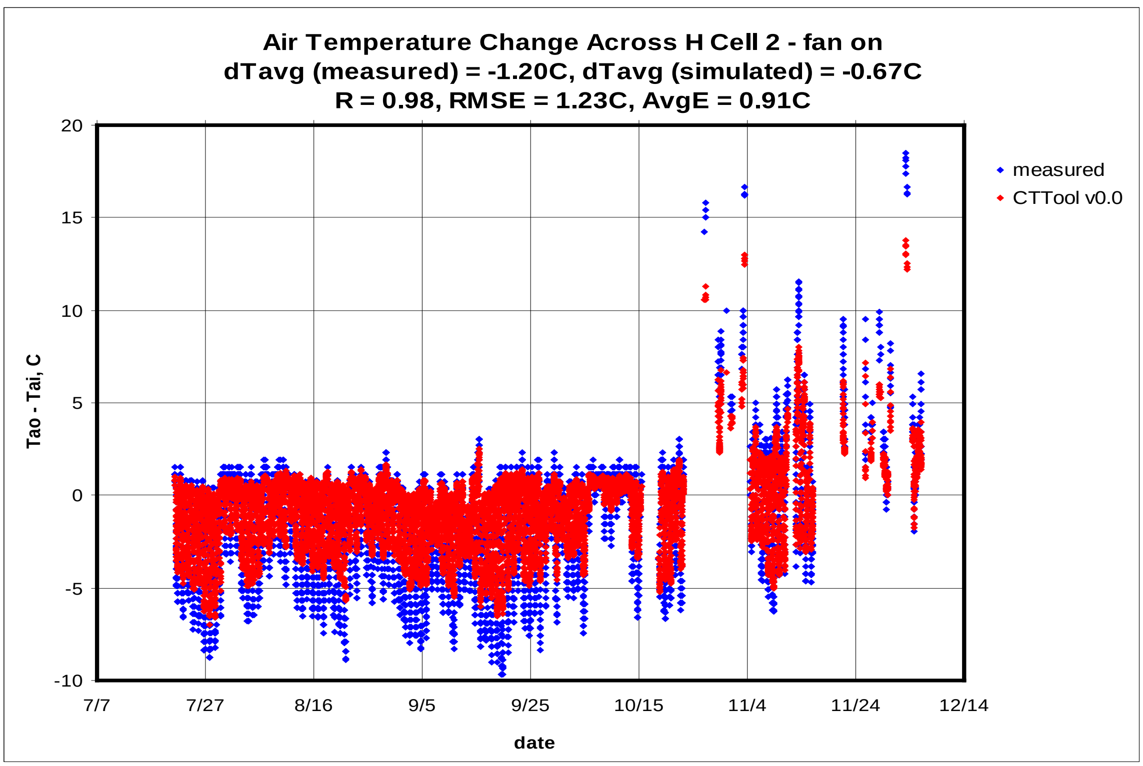

Water Temperature Change Across H Cell 2 - fan off
dTavg (measured) = 1.31C, dTavg (simulated) = 1.30C
R = 0.51, RMSE = 0.85C, AvgE = 0.69C (no wind)
Twi - Two, C
date
9/25
10/5
10/15
10/25
11/4
11/14
11/24
12/4
12/14
-1
0
1
2
3
4
5
6
measured
CTTool v1.0

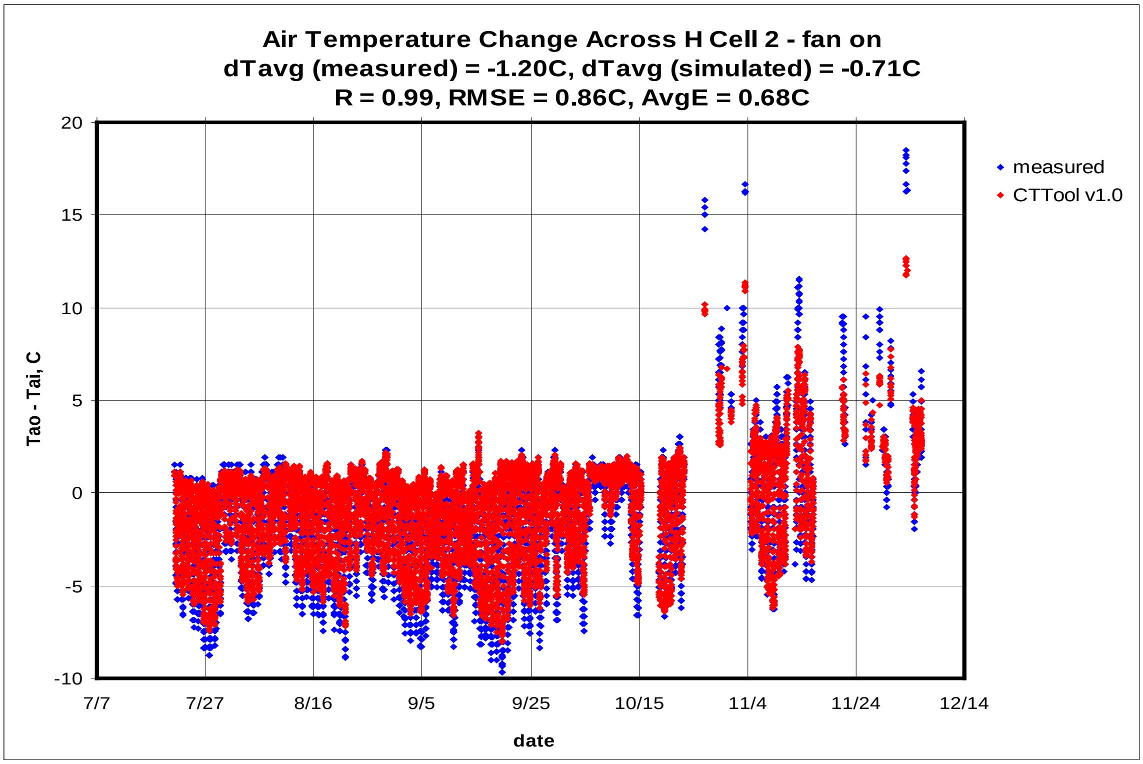

Air Temperature Change Across H Cell 2 - fan off
dTavg (measured) = 7.31C, dTavg (simulated) = 4.49C
R = 0.97, RMSE = 3.59C, AvgE = 3.08C
Tao - Tai, C
date
9/25
10/5
10/15
10/25
11/4
11/14
11/24
12/4
12/14
-10
-5
0
5
10
15
20
25
measured
CTTool v0.0


Air Temperature Change Across H Cell 2 - fan off
dTavg (measured) = 7.31C, dTavg (simulated) = 9.33C
R = 0.97, RMSE = 2.47C, AvgE = 2.21C (no wind)
Tao - Tai, C
date
9/25
10/5
10/15
10/25
11/4
11/14
11/24
12/4
12/14
measured
CTTool v1.0


Water Temperature Change Across H Cell 2 - fan on
dTavg (measured) = 3.55C, dTavg (simulated) = 3.48C
R = 0.92, RMSE = 0.56C, AvgE = 0.45C
Twi - Two, C
date
7/7
7/27
8/16
9/5
9/25
10/15
11/4
11/24
12/14
measured
CTTool v0.0


Water Temperature Change Across H Cell 2 - fan on
dTavg (measured) = 3.55C, dTavg (simulated) = 2.99C
R = 0.85, RMSE = 0.91C, AvgE = 0.77C
Twi - Two, C
0
2
4
6
8
10
12
14
16
7/7
7/27
8/16
9/5
9/25
10/15
11/4
11/24
12/14
date
measured
CTTool v1.0


Air Temperature Change Across H Cell 2 - fan on
dTavg (measured) = -1.20C, dTavg (simulated) = -0.67C
R = 0.98, RMSE = 1.23C, AvgE = 0.91C
Tao - Tai, C
-10
-5
0
5
10
15
20
7/7
7/27
8/16
9/5
9/25
10/15
11/4
11/24
12/14
date
measured
CTTool v0.0



4.3 A-Area Cooling Tower Benchmarking

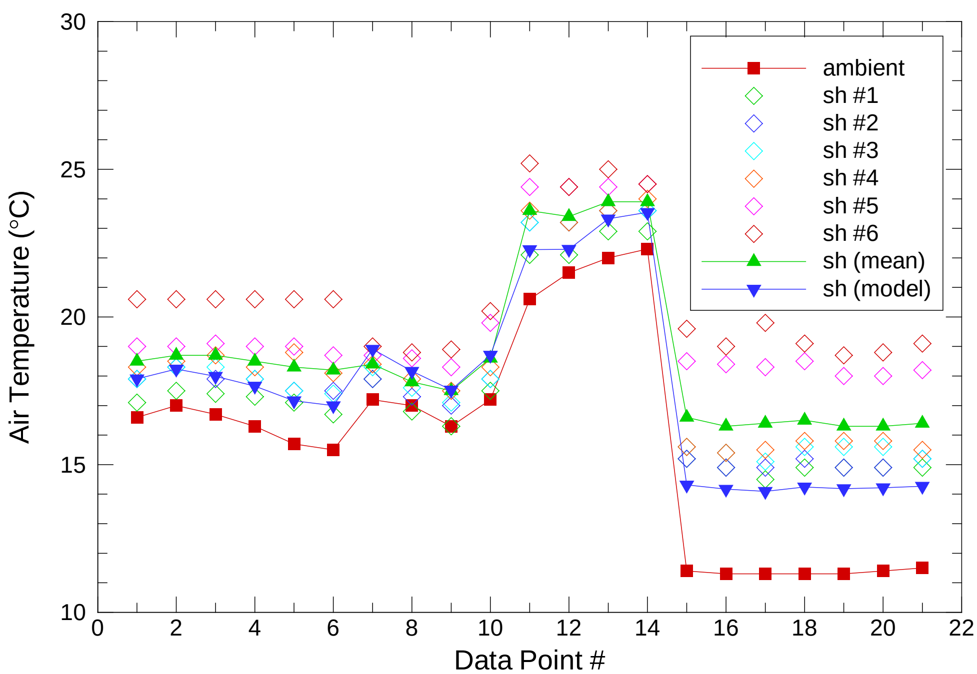


Figure 4-1. A-Area cross-flow cooling tower air temperatures (fan on).

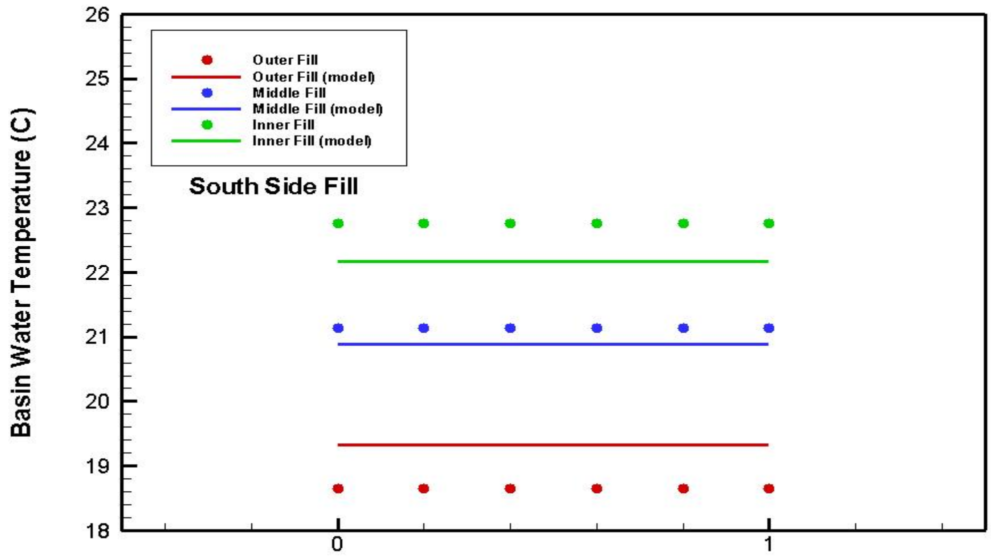


Figure 4-2. A-Area cross-flow cooling tower basin water temperatures (fan on).

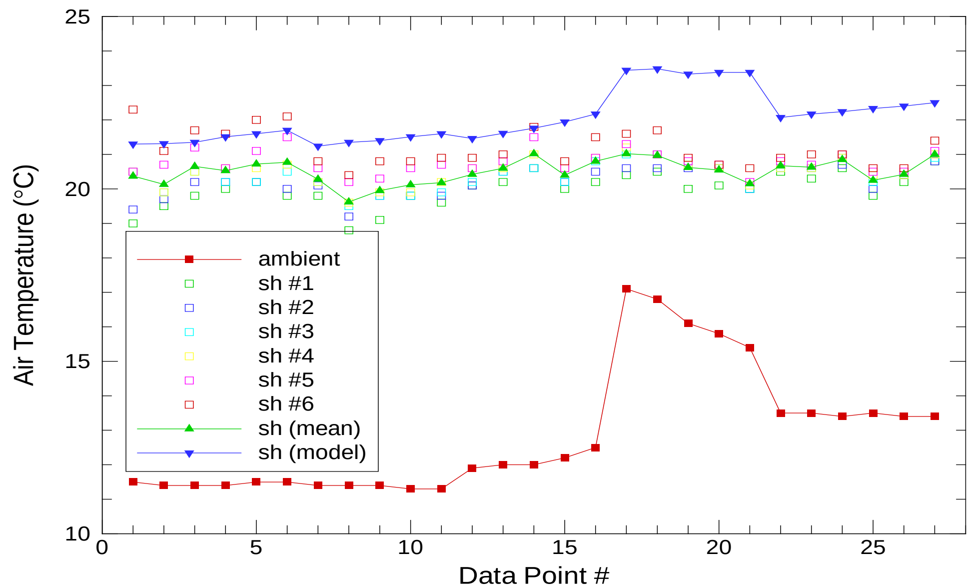


Figure 4-3. A-Area cross-flow cooling tower air temperatures (fan off).

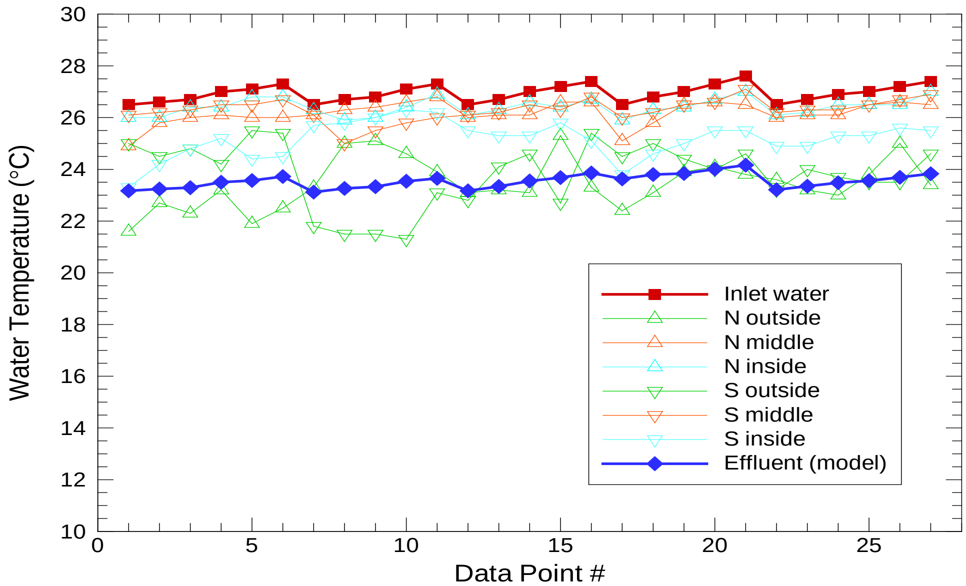


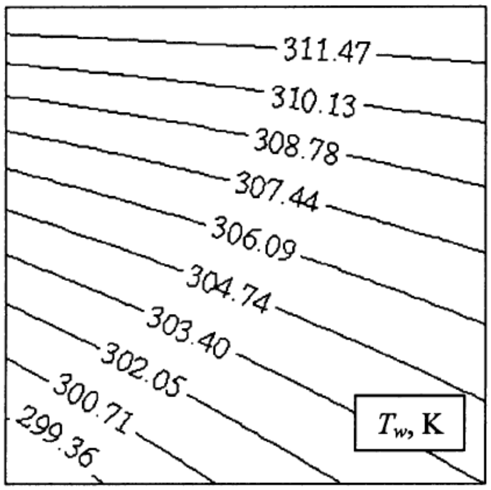
Figure 4-4. A-Area cross-flow cooling tower water temperatures (fan off)

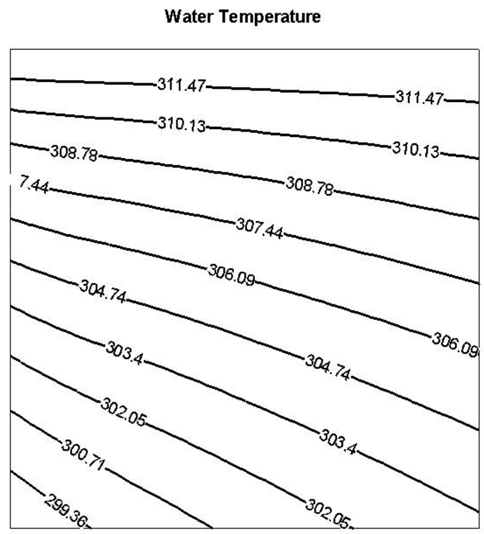
4.4 Comparison of CTTool to Kloppers and Kroger Cross-fill Model Results

During a crossflow fill performance test, the following variables were measured.

- Atmospherical pressure p_{atm} = 101712.27 Pa
- Air inlet temperature T_{ai} = 9.7°C (282.85 K)
- Wet-bulb temperature T_{wb} = 8.23°C (281.38 K)
- Dry air mass flowrate m_a = 4.134 kg/s
- Water inlet temperature T_{wi} = 39.67°C (312.82 K)
- Water outlet temperature T_{wo} = 27.77°C (300.92 K)
- Inlet water mass flowrate m_w = 3.999 kg/s

The following plots show a comparison between the Kloppers and Kroger model and CTTool. There is excellent agreement between the two models.





K and K CTTool

Figure 4-4. Comparison of Klopppers/Kroger and CTTool water temperature distribution.

5.0 References

1. Garrett, A. J., M. J. Parker, E. Villa-Aleman: “2004 Savannah River Site Cooling Tower Collection”. SRNL-DOD-2005-07, Savannah River National Laboratory, Aiken, SC, 29808.
2. Louis, J. F., 1979: “A parametric model of vertical eddy fluxes in the atmosphere”. Boundary-Layer Meteorlogy, **17**, 187-202.
3. Tennessee Valley Authority, 1972: “Heat and mass transfer between a water surface and the atmosphere”. Water Resources Research Laboratory Report #14, O-6803, Norris, Tennessee.
4. Bird, R. b., W. E. Stewart, E. N. Lightfoot, “Transport Phenomena”, John Wiley and Sons.
5. Montanaro, M., “Radiometric Modeling of Mechanical Draft Cooling Towers to Assist in the Extraction of their Absolute Temperature from Remote Thermal Imagery,” Ph.D dissertation, Rochester Institute of Technology, May 2009.

Appendix A CTTool v1.0 User's Manual

A.1 Data structure

The input and output files associated with the CTTool v1.0 code and their contents are described below.

A.2 Super file

The CTTool super file is a special type of file used to organize the individual files for input and output operations. The super file is a text file that contains the names of input/output files. The super file is read from the command line (UNIT=5). The first line of the super file is an identifier card, "CTToolSup". After the identifier line, each subsequent line is preceded by a four-letter category code and a filename. The category code and filename have to be enclosed in single or double quotes. The MINP, SMRS, CFCT or XFCT categories are required. The other categories are specified based on the state of the simulation and output options. Table A-1 shows the format of a typical super file.

Table A-1. CTTool Super File Format

Category	File Name
CTToolSup	
'MINP'	'SRNL20Jun05G09.minp'
'SMRS'	'SRNL20Jun05G09.smrs'
'CFCT'	'SRNL20Jun05G09.cfct'
'LUTB'	'SRNL20Jun05G09.lutb'
'MOUT'	'SRNL20Jun05G09.mout'
'DIAG'	'SRNL20Jun05G09.diag'

A.3 File content and organization

Table A-2 summarizes the input and output (I/O) files specified within the CTTool super file. The detailed content and organization of each file is presented in the next section.

CTTool uses list-directed **READ** statements to process numeric data in the model input, surface meteorology and remote sensing data, counterflow cooling tower parameters, cross-flow cooling tower parameters, sensor Look-Up Table and cooling tower benchmarking data. Therefore, there are no data formatting requirements and the data associated with a given **READ** statement may occupy multiple lines in the input files. Data groups are delineated by required comment lines that serve the purpose of annotating the input.

Besides a main output file and optional diagnostic file, CTTool can create an additional output files intended for Tecplot™ post-processing.

Table A-2. Summary of CTTool Input and Output Files

File	Unit	I/O	Category
super file	5	input	
model input	10	input	MINP
surface meteorology and remote sensing data	11	input	SMRS
counterflow cooling tower parameters	12	input	CFCT
cross-flow cooling tower parameters	13	input	XFCT
sensor Look-Up Table	14	input	LUTB
F, H or A-Area cooling tower benchmarking data	97	input	BMRK (roi= -2 to -4)
model output	20	output	MOUT
diagnostic output	21	output	DIAG
CTModelTemps.plt	2	output	DIAG (roi=1)
imgxxx.out	3	output	DIAG (roi=1)
matid0.plt	3	output	DIAG (roi=1)
matid.plt	3	output	DIAG (roi=1)
raytracing.txt	4	output	DIAG (roi=1)
Water-side.plt	90	output	CFCT, DIAG
Air-side.plt	91	output	CFCT, DIAG
Le-side.plt	92	output	CFCT, DIAG
Water-side-1.plt	90	output	XFCT, DIAG
Air-side-1.plt	91	output	XFCT, DIAG
Le-side-1.plt	92	output	XFCT, DIAG
Water-side-2.plt	93	output	XFCT, DIAG
Air-side-2.plt	94	output	XFCT, DIAG
Le-side-2.plt	95	output	XFCT, DIAG
F, H or A-Area cooling tower water temperatures	98	output	H2OT (roi= -2 to -4)
F, H or A-Area cooling tower air temperatures	99	output	AIRT (roi= -2 to -4)

A.4 Model input

The model input file is specified in the 'MINP' category of the superfile and is divided into 4 groups and arranged as follows:

1. Problem Description
2. Model Options
3. Operating Conditions
4. Tower Location

A description of the input variables and data formats is presented below. The user should keep in mind the following items when preparing the main input file.

- The data associated with a given **READ** statement is termed a "data record" in the discussion below.
- A comment line is required before most data records as described below. A comment line can be of any length.
- CTTool uses list-directed **READ** statements to process numeric data. Therefore, there are no data formatting requirements and the data associated with a given **READ** statement may occupy multiple lines in the model input file.

The following data records are required as indicated:

Group 1

1. Problem Description

```
comment
ntitle
title(1)
   :
title(ntitle)
```

ntitle: Number of title lines.

title: Title character array $(1 \le i \le \text{ntitle})$. Each title line cannot be greater than 128 characters and must be enclosed in single or double quotes.

Group 2

2. Model Options

```
comment
ctty    ctmx   roi     lut     nobs
```

ctty: Type of cooling tower;
= 0 counterflow cooling tower,

= 1 cross-flow cooling tower.

ctmx: Maximum number of cooling towers.

roi: Region of interest with respect to sensor;
= -4 none, A-Area cooling tower benchmarking,
= -3 none, F-Area cooling tower benchmarking,
= -2 none, H-Area cooling tower benchmarking,
= -1 none, cooling tower calculation only,
= 0 single cooling tower throat only,
= 1 single or multi-cells (throat and exposed materials).

lut: Sensor Look-Up Table utilized;
= -1 sensor delta-T (radiometer-measured throat temperature (assuming an emissivity of 1) with ambient air temperature subtracted out,
= 0 mixed ROI (MODTRAN/DIRSIG),
= 1 cavity-only ROI (MODTRAN/DIRSIG).

nobs: Number of observations or images to process.

Group 3

3. Operating Conditions

```
comment
fan(1)..............fan(ctmx)
```

fan: Fan operation for each cooling tower;
= 0 fan is off,
= 1 fan is on.

if counterflow cooling tower (ctty = 0) then

```
comment
mfwi   mfai   rlg   twi
```

mfwi: Inlet mass flow rate of water to CFCT, kg/s;
< 0 compute deck area-based estimate.

mfai: Inlet mass flow rate of air to CFCT, kg/s.

rlg: Ratio of liquid to gas mass flow rates;
= 1 use input value of mfai, otherwise compute as mfwi/rlg.

twi: Inlet (hot) water temperature to CFCT, C;
actual temperature for roi = -1, otherwise initial guess.

else cross-flow cooling tower (ctty = 1)

comment
mfwi mfaS1i mfaS2i rlg twi

mfwi: Inlet mass flow rate of water to XFCT, kg/s;
< 0 compute deck area-based estimate.

mfaS1i: Side 1 Inlet mass flow rate of air to XFCT, kg/s.

mfaS2i: Side 2 Inlet mass flow rate of air to XFCT, kg/s.

rlg: Ratio of liquid to gas mass flow rates;
= 1 use input value of mfai, otherwise compute as 0.5*mfwi/rlg for each side.

twi: Inlet (hot) water temperature to XFCT, C;
actual temperature for roi = -1, otherwise initial guess.

end if

Group 4

4. <u>Tower Location</u>

comment
rlatd rlond phi

rlatd: Latitude in degrees.

rlond: Longitude in degrees.

phi: Short axis orientation of cooling tower wrt true north in degrees.

The following is an example.

```
/Problem Description                                                    /
 2
 'Simulation of the SRS F-Area Counterflow Cooling Tower cells'
 'during natural draft operation (05/10/04 to 08/02/04) 8079 points'
/ctty     ctmx     roi     lut    nobs                                 /
 0        1        -3      -1     1
/fan                                                                    /
 0
/mfwi     mfai     rlg     twi                                          /
 1.       160.     1.      26.94
/rlatd    rlond    phi                                                  /
 33.      -81.6    -36.3
```

A.5 Surface Meteorology and Remote Sensing Data

The surface meteorology and remote sensing data file is specified in the super file under the 'SMRS' category. This data file is used to provide surface meteorology in the proximity of the cooling towers of interest as well as sensor parameters for each image to be processed. The structure of the data file is as follows:

The following block of data is repeated nobs times:

```
comment
j      wind_d(i)    wind_s(i)    air_t(i)     dew_p(i)     cloud_c(i)
       cloud_h(i)   atm_p(i)
comment
       roi_t(i)     sensor_t(i)  sensor_z(i)  sensor_a(i)
comment
       year_(i)     zday_(i)     ztime_(i)
```

j: Image or observation number.

wind_d: Wind direction in from north to east degrees (0 to 360).

wind_s: Wind speed in m/s.

air_t: Ambient air temperature in C.

dew_p: Ambient dew point in C.

cloud_c: Cloud cover (0=clear, 1=total overcast).

cloud_h: Cloud height in km.

atm_p: Atmospheric or station pressure in mb.

roi_t: Sensor region-of-interest temperature in C (roi = 1).

sensor_t: Sensor target temperature with ambient air temperature subtracted out in C (roi > -1 and lut = -1).

sensor_z: Sensor zenith angle in degrees.

sensor_a: Sensor azimuth angle in degrees.

year_: Observation year.

zday_: Observation Julian day.

ztime_: Observation Greenwich (Z) time.

The following is an example.

```
/image   wdir    wspd    tdb     tdp     clcv    clht    patm    /
 1       0.      0.      24.4    20.79   0.      0.      1007.41
/troi    ssdt    ssza    ssaa                                    /
 0.      0.      0.      0.
/year    day     time                                            /
 2005    171     22.28
```

A.6 Counterflow Cooling Tower Parameters

The counterflow cooling tower parameters data file is specified in the super file under the ‘CFCT’ category. This data file is used to provide counterflow cooling tower geometry, heat/mass transfer parameters, solid decking heat transfer parameters and mesh discretization in the fill section. The structure of the data file is as follows:

```
comment
dkxw   dkyw   dkht   fsht   fsid
```

dkxw: Cooling tower deck width in x-direction (long axis) in m.

dkyw: Cooling tower deck width in y-direction (short axis) in m.

dkht: Cooling tower deck height above ground in m.

fsht: Fan shroud height in m.

fsid: Fan shroud inner diameter in m.

```
comment
flht   rsht   bsht   detk
```

flht: Fill section height in m.

rsht: Rain section height in m.

bsht: Water basin section height in m.

detk: Drift eliminator thickness in m.

comment mlthtc mltmtc mltfil

mlthtc: Heat transfer coefficient multiplier.

mltmtc: Mass transfer coefficient multiplier.

mltfil: Fill section frictional loss multiplier.

comment deqv flfa flsa wtsa ksum

deqv: Fill section equivalent diameter in m.

flfa: Fill section flow area in m^2.

flsa: Fill section surface area in m^2.

wtsa: Wetted fraction of fill section surface area.

ksum: Sum of loss coefficients above fill section.

comment dktk dkem dkdn dkcp dktc

dktk: Deck thickness in m.

dkem: Deck emissivity.

dkdn: Deck material density in gm/m^3.

dkcp: Deck material specific heat in cal/gm-K.

dktc: Deck thermal conductivity in cal/s-m-K.

comment nfsvc

nfsvc: Number of vertical cells in fill section.

The following is an example.

```
/dkxw     dkyw     dkht     fsht     fsid                              /
```

```
 8.5      8.5      10.      3.0      4.1
/flht     rnht     bsht     detk                                        /
 2.013    1.633    1.168    0.1524
/mlthtc   mltmtc   mltfil                                               /
 1.       1.       4.
/deqv     flfa     flsa     wtsa     ksum                               /
 0.0381   67.29    14221.   1.       10.
/dktk     dkem     dkdn     dkcp     dktc                               /
 0.003    0.944    2.5d+6   0.26     0.01
/nfsvc                                                                  /
 49
```

A.7 Cross-flow Cooling Tower Parameters

The cross-flow cooling tower parameters data file is specified in the super file under the ‘XFCT’ category. This data file is used to provide cross-flow cooling tower geometry, heat/mass transfer parameters, solid decking heat transfer parameters and mesh discretization in the fill section. The structure of the data file is as follows:

```
comment
dkxw   dkyw   dkht    fsht    fsid
```

dkxw: Cooling tower deck width in x-direction (long axis) in m.

dkyw: Cooling tower deck width in y-direction (short axis) in m.

dkht: Cooling tower deck height above ground in m.

fsht: Fan shroud height in m.

fsid: Fan shroud inner diameter in m.

```
comment
flht    fldp    flwt    detk
```

flht: Fill section height in m.

fldp: Fill section depth in m.

flwt: Fill section width in m.

detk: Drift eliminator thickness in m.

```
comment
dpvel   dpdia   mlthtc  mltmtc
```

dpvel: Droplet velocity in fill section in m/s.

dpdia: Droplet diameter in fill section in m.

mlthtc: Heat transfer coefficient multiplier.

mltmtc: Mass transfer coefficient multiplier.

```
comment
kfil    kmix
```

kfil: Fill section loss coefficient.

kmix: Mixture section and fan shroud loss coefficient.

```
comment
dktk    dkem   dkdn    dkcp    dktc
```

dktk: Deck thickness in m.

dkem: Deck emissivity.

dkdn: Deck material density in gm/m^3.

dkcp: Deck material specific heat in cal/gm-K.

dktc: Deck thermal conductivity in cal/s-m-K.

```
comment
nxfhc   nxfvc
```

nxfhc: Number of horizontal cells in each fill section.

nxfvc: Number of vertical cells in each fill section.

The following is an example.

```
/dkxw     dkyw     dkht     fsht     fsid                              /
 9.2      13.7     7.6      1.8      6.4
/flht     fldp     flwt     detk                                       /
```

```
 6.4      3.2      8.6      0.146
/dpvel    dpdia    mlthtc   mltmtc                                /
 1.395    4.d-3    1.5      1.5
/kfil     kmix                                                    /
 11.      11.
/dktk     dkem     dkdn     dkcp     dktc                         /
 0.0254   0.944    5.5d+5   0.29     0.03
/nxfhc    nxfvc                                                   /
 49       49
```

A.9 Sensor Look-Up Table (roi = 0 and lut >= 0)

The sensor look-up table data file is specified in the super file under the 'LUTB' category. This data file is used to provide regression coefficients for the mixed and cavity region-of-interest temperature error. A vector of predictor estimates for a given image is also specificed. The regression equation for the mixed ROI temperature error is

$$\hat{y}_1 = \text{xmix}(0) + \sum_{i=1}^{7} \text{xmix}(i)\text{xvec}(i) \qquad \text{(A-1)}$$

Similarly, the regression equation for the cavity ROI temperature error is

$$\hat{y}_2 = \text{xcav}(0) + \sum_{i=1}^{7} \text{xcav}(i)\text{xvec}(i) \qquad \text{(A-2)}$$

The structure of the data file is as follows:

comment desc(1) desc(2) desc(3)

desc: Sensor description. Each line limited to 128 characters.

comment xmix(0:7)

xmix: Regression coefficients for the mixed ROI LUT.

```
comment
xcav(0:7)
```

xcav: Regression coefficients for the cavity ROI LUT.

```
comment
xvec(1:7)
```

xvec: Vector of predictor estimates for a given image.

xvec(1) = cooling tower external temperature, K
xvec(2) = fan blade emissivity
xvec(3) = effective sky temperature, K
xvec(4) = sensor zenith angle, deg
xvec(5) = ambient air temperature, K
xvec(6) = ambient dew point temperature, K
xvec(7) = plume path length (sensor line-of-sight), m

The following is an example.

```
/Sensor description/
 'LUT generated for SC2000 camera'
 'GSD = 0.13 meters (350 foot altitude)'
 'Spectral range = 7.6-13.5 microns'
/Mixed ROI:  x0 x1 x2 x3 x4 x5 x6 x7/
 -17.5961  -0.0340  10.7930  0.0349  -0.0075  0.0223  0.0016  0.0021
/Cavity ROI: x0 x1 x2 x3 x4 x5 x6 x7/
  -6.3769  -0.0273   4.1551  0.0138  -0.0049  0.0220 -0.0006 -0.0003
/x1       x2     x3     x4    x5       x6       x7 /
 293.68   0.90   264.   29.   296.39   293.17   8.
```

A.10 F. H or A-Area Cooling Tower Benchmarking Data (roi <= -2)

The F, H or A-Area cooling tower benchmarking data file is specified in the super file under the ‘BMRK’ category. This data file is used to provide operating and meteorological data for cooling tower tests conducted at the Savannah River Site from 2004 to 2005. The predicted cooling tower air and water temperature changes from the earlier version of CTTool are also provided in the data file. The meteorological data specified in the ‘SMRS’ category is ignored. Each cooling tower dataset has a different file format.

The structure of the data file for the A-Area cooling tower dataset (roi = -4) is as follows:

windopt											
tcase	date	tao	dum	tdb	dum	two	twi	patm	wdir	wspd	mfwi
	twb	tdp	vexit	dtwobs		dtwv0		dtaobs		dtav0	

The structure of the data file for the F-Area cooling tower dataset (roi = -3) is as follows:

windopt		vexit									
date	tao1	tao2	dum	dum	dum	two	dum	twi	tdb	tdp	patm
	dum	wdir	wspd	dtwobs		dtwv0		dtaobs		dtav0	

The structure of the data file for the H-Area cooling tower dataset (roi = -2) is as follows:

windopt		vexit								
date	tao	dum	tdb	dum	two	twi	patm	wdir	wspd	cwflow
	dum	twb	tdp	dum	dum	dum	dum	dtwobs		dtwv0
	dtaobs		dtav0							

windopt: wind option for fans off, either natural draft or natural draft/wind aided.
= 0 natural draft only,
= 1 natural draft/wind aided

vexit exit air speed (fan on), m/s.

tcase: test case identifier (i.e. FastFan1), 8 characters.

date: number of days counting from January 1, 1900, xxxxx.xxxxx format.

tao exit air temperature. C.

tao1 exit air temperature (Tidbit). C.

tao2 exit air temperature (Hobo). C.

dum dummy value, not used.

tdb dry-bulb temperature, C.

two exit water temperature, C.

twi inlet water temperature, C.

patm station pressure, mb.

wdir wind direction, degrees.

wspd	wind speed, m/s.
cwflow	H-Area cooling water flow (4 cells), m^3/s
mfwi	inlet mass flow rate of water, kg/s.
twb	wet-bulb temperature, C.
tdp	dew point temperature, C.
dtwobs	observed water temperature change, C.
dtwv0	CTTool v0 predicted water temperature change, C.
dtaobs	observed air temperature change, C.
dtav0	CTTool v0 predicted air temperature change, C.

A.11 Model output

The model output file is specified in the super file under the ‘MOUT’ category. The model output file for a cross-flow cooling tower is listed below.

```
                   XXXX  XXXXXXX XXXXXXX                   XX
                  X    X X  X  X X  X  X                    X
                 X          X       X                       X
                 X          X       X     XXXXX   XXXXX     X
                 X          X       X    X     X X     X    X
                 X          X       X    X     X X     X    X
                 X          X       X    X     X X     X    X
                  X    X    X       X    X     X X     X    X
                   XXXX    XXX     XXX    XXXXX   XXXXX   XXXXX

                                   #              ###
                         #    #   ##             #   #
                         #    #  # #            #     #
                         #    #    #            #     #
                         #    #    #      ###   #     #
                          #  #     #      ###    #   #
                           ##    #####    ###     ###


Savannah River National Laboratory

Configuration Status:   Testing
Status of Code Changes: None
Current Date: 12-01-2009
```

```
Current Time: 12:45:40

========================= Problem Description ===========================

Simulation of the SRS F-Area Counterflow Cooling Tower cells
during natural draft operation (05/10/04 to 08/02/04) 8079 points

============================ Model Options ==============================

type of cooling tower ................................ (ctty) =     0
  ctty = 0, counterflow cooling tower
       = 1,  cross-flow cooling tower
maximum number of cooling towers ...................... (ctmx) =     1
region of interest (ROI) wrt sensor ................... (roi) =    -3
  roi = -1, none. cooling tower calculation only
  roi =  0, single CT throat only
      =  1, multi cell (throat and exposed materials)
sensor Look-Up-Table utilized (ROI = 0) ................ (lut) =    -1
  lut = -1, sensor delta-T
      =  0, mixed  ROI
      =  1, cavity-only ROI
number of observations or images to process ........... (nobs) =     1

========================= Operating Conditions ==========================


fan operation for cooling tower #  1 .................. (fan) =     0
  fan = 0, fan is off
      = 1, fan is on
mass flow rate of water (kg/s) ....................... (mfwi) =  1.000E+00
  mfwi < 0., compute deck area-based estimate
mass flow rate of air to CFCT (kg/s) ................. (mfai) = 1.600E+02
ratio of liquid to gas mass flow rates ................ (rlg) = 1.000E+00
  rlg = 1., use input value of mfai, otherwise compute as mfwi/rlg
initial inlet water temperature (c) ................... (twi) = 2.694E+01

============================ Tower Location ============================

latitude in degrees ................................. (rlatd) =  3.30E+01
longitude in degrees ................................ (rlond) = -8.16E+01
short axis orientation of cooling tower (wrt tn) ....... (phi) = -3.63E+01

================== Counterflow Cooling Tower Parameters =================
```

```
cooling tower deck width in x-dir (m) ................ (dkxw) = 8.500E+00
cooling tower deck width in y-dir (m) ................ (dkyw) = 8.500E+00
cooling tower deck height above ground (m) ........... (dkht) = 1.000E+01
fan shroud height (m) ................................ (fsht) = 3.000E+00
fan shroud inner diameter (m) ........................ (fsid) = 4.100E+00
fan shroud flow area (m^2) ........................... (fsfa) = 1.320E+01

fill section height (m) .............................. (flht) = 2.013E+00
rain section height (m) .............................. (rsht) = 1.633E+00
basin section height (m) ............................. (bsht) = 1.168E+00
drift eliminator thickness (m) ....................... (detk) = 1.524E-01

heat transfer coefficient multiplier ............... (mlthtc) = 1.000E+00
mass transfer coefficient multiplier ............... (mltmtc) = 1.000E+00
fill section frictional loss multiplier ............ (mltfil) = 4.000E+00

fill equivalent diameter (m) ......................... (deqv) = 3.810E-02
height for natural convection (m) .................... (dznc) = 1.183E+01
fill section flow area (m^2) ......................... (flfa) = 6.729E+01
fill section surface area (m^2) ...................... (flsa) = 1.422E+04
rain section inlet flow area (m^2) ................... (rsfa) = 7.225E+01
wetted fraction of fill surface area ................. (wfsa) = 1.000E+00
sum of loss coefficients above fill .................. (ksum) = 1.000E+01

deck thickness (m) ................................... (dktk) = 3.000E-03
deck emissivity ...................................... (dkem) = 9.440E-01
deck material density (gm/m^3) ....................... (dkdn) = 2.500E+06
deck material specific heat (cal/gm-K) ............... (dkcp) = 2.600E-01
deck thermal conductivity (cal/s-m-K) ................ (dktc) = 1.000E-02

number of vertical cells in fill section ............ (nfsvc) =    49

=============== Meteorological/remote sensing data summary ===============

number of data points =    1

wind direction in from North to East degrees (0-360)
wind speed in m/s
air temperature in c
dew point in c
cloud cover (0=clear, 1=total overcast)
cloud height in km
```

```
atmospheric pressure in mb
sensor ROI temperature in c
sensor delta-t in c (no LUT)
sensor zenith angle in deg
sensor azimuth angle in deg
observation year
observation zday
observation ztime

=========================== image number   200 ===========================

wind speed     2.67 m/s
wind direction    189.8 deg
delta-p wind    3.564 Pa
local time    17.28
zenith angle    0.0

Cooling tower #  1 running with fan off
inlet  water temp 297.98 K, 24.83 C
outlet water temp 296.18 K, 23.03 C
enthalpy change-water   346.78     kw,   82900.     cal/s
enthalpy change-air    -349.66     kw,  -83589.     cal/s
station pressure 101286.0 Pa
ambient vapor pressure   2086.3 Pa
ambient saturated vapor pressure   3300.6 Pa
ambient dry-bulb  temp 298.98 K, 25.83 C
ambient wet-bulb  temp 295.03 K, 21.88 C
ambient dew point temp 291.34 K, 18.19 C
ambient humidity ratio   1.3081E-02 kg H2O/kg air
ambient relative humidity  63.21 %
approach to wet-bulb temp  1.15 C
cooling range  1.80 C
cooling tower efficiency  61.1 %
inlet water mass flowrate   44.03 kg/s,  700.00 gpm
exit  water mass flowrate   43.89 kg/s,  697.20 gpm
evaporation loss    0.15 kg/s
dry air mass flowrate     24.4     kg/s
dry air exhaust velocity  1.562 m/s
exit vapor pressure   3028.3 Pa
exit saturated vapor pressure   3068.6 Pa
exit dry-bulb  temp 297.74 K, 24.59 C
exit wet-bulb  temp 297.58 K, 24.43 C
exit dew point temp 297.52 K, 24.37 C
```

```
exit humidity ratio   1.9169E-02
exit relative humidity  98.68 %

total enthalpy change-water   346.78     kw
total enthalpy change-air    -349.66     kw
mixed-mean exit water temp 296.18 K, 23.03 C
```

A.12 Diagnostics

The diagnostic log file is specified in the super file under the ‘DIAG’ category. This file provides the following diagnostic information

- Array name allocated and calling subroutine.
- Array size allocated and running total in MB.
- Error messages.

The following is an example.

```
                  Header: Array      title allocated     0.000 out of   0.000 MB
     OperatingConditions: Array        fan allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array     wind_d allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array     wind_s allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array      air_t allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array      dew_p allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array    cloud_c allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array    cloud_h allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array      atm_p allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array      roi_t allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array   sensor_t allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array   sensor_z allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array   sensor_a allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array      year_ allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array      zday_ allocated     0.000 out of   0.000 MB
      ReadSurfMetrRSData: Array     ztime_ allocated     0.000 out of   0.000 MB
      CFCTInitialization: Array      hrcfp allocated     0.000 out of   0.001 MB
      CFCTInitialization: Array      mwcfp allocated     0.000 out of   0.001 MB
      CFCTInitialization: Array      tacfp allocated     0.000 out of   0.002 MB
      CFCTInitialization: Array      twcfp allocated     0.000 out of   0.002 MB
      CFCTInitialization: Array       hrcf allocated     0.000 out of   0.002 MB
      CFCTInitialization: Array       mwcf allocated     0.000 out of   0.003 MB
      CFCTInitialization: Array       tacf allocated     0.000 out of   0.003 MB
      CFCTInitialization: Array       twcf allocated     0.000 out of   0.004 MB
      CFCTInitialization: Array      maout allocated     0.000 out of   0.004 MB

****Max iterations exceeded in CFCTFanOff****
```

```
****Max iterations exceeded in CFCTFanOff****
```

A.13 F. H or A-Area Cooling Tower Benchmarking Temperatures (roi <= -2)

The F, H or A-Area cooling tower benchmarking temperature data files are specified in the super file under the ‘AIRT’ and ‘H2OT’ categories for air and water temperature changes, respectively. Each data file contains the observed, CTTool v0 and CTTool v1 air or water temperature changes for each simulation date.

The structure of the data file for the air temperature changes is:

date	dtaobs	dtav0	dtav1

The structure of the data file for the water temperature changes is:

date	dtwobs	dtwv0	dtwv1

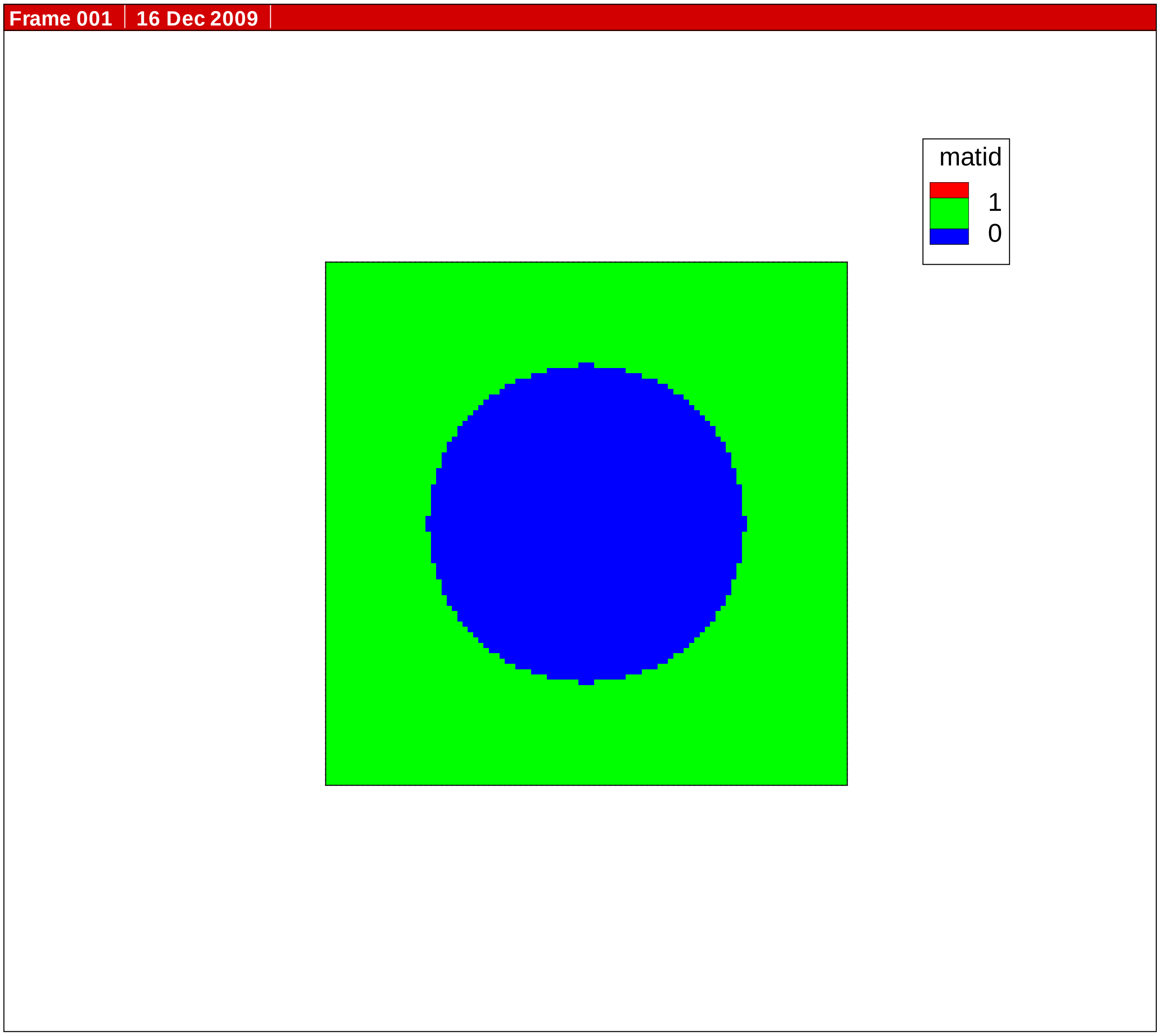
date:	number of days counting from January 1, 1900 (i.e. 39029.07639).
dtaobs	observed air temperature change, C.
dtav0	CTTool v0 predicted air temperature change, C.
dtav1	CTTool v1 predicted air temperature change, C.
dtwobs	observed water temperature change, C.
dtwv0	CTTool v0 predicted water temperature change, C.
dtwv1	CTTool v1 predicted water temperature change, C.

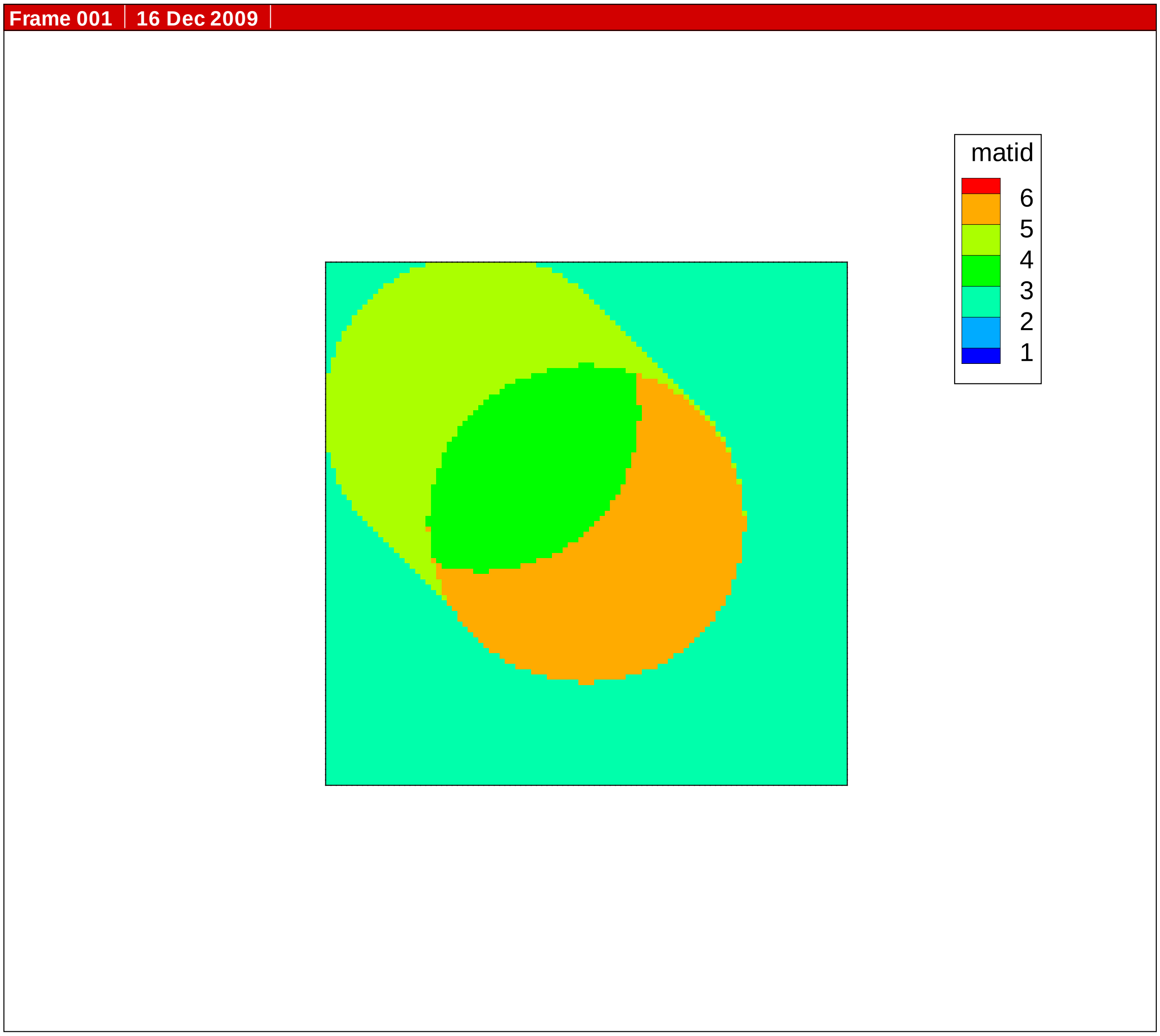
An example of the air temperature change datafile is:

```
39029.07639    8.87    7.22   11.22
39029.15972    8.87    7.22   11.12
39029.22569    8.76    7.38   11.28
39029.29514    8.76    7.38   11.66
39029.37500    8.49    6.99   10.67
39029.41667    8.49    6.99   10.67
39029.66319    4.69    4.81    5.95
39029.71181    4.69    4.81    5.93
39029.79861    7.06    6.15    8.95
39029.86806    7.06    6.15    7.18
39056.08333   15.41   12.17   19.25
39056.16667   15.41   12.17   12.55
```

A.14 Solid Deck Raytracing (‘DIAG’ and roi = 1)

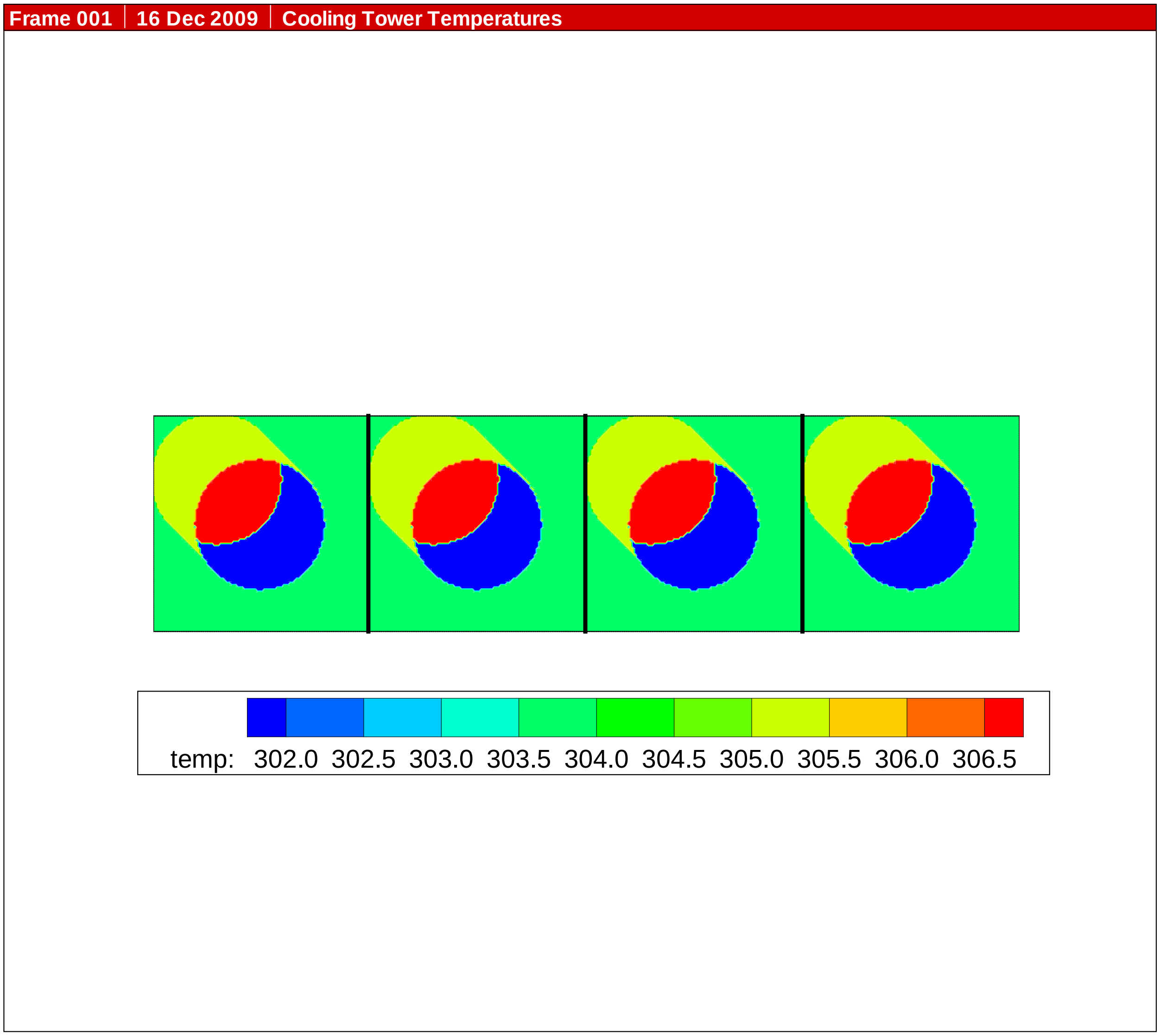
The solid deck raytracing results are written to Tecplot files matid0.plt and matid.plt. The first file shows the throat and other materials. The second file differentiates the various materials from the sensor line-of-sight. The following pictures illustrate these files.


Frame 001
16 Dec 2009
matid
1
0

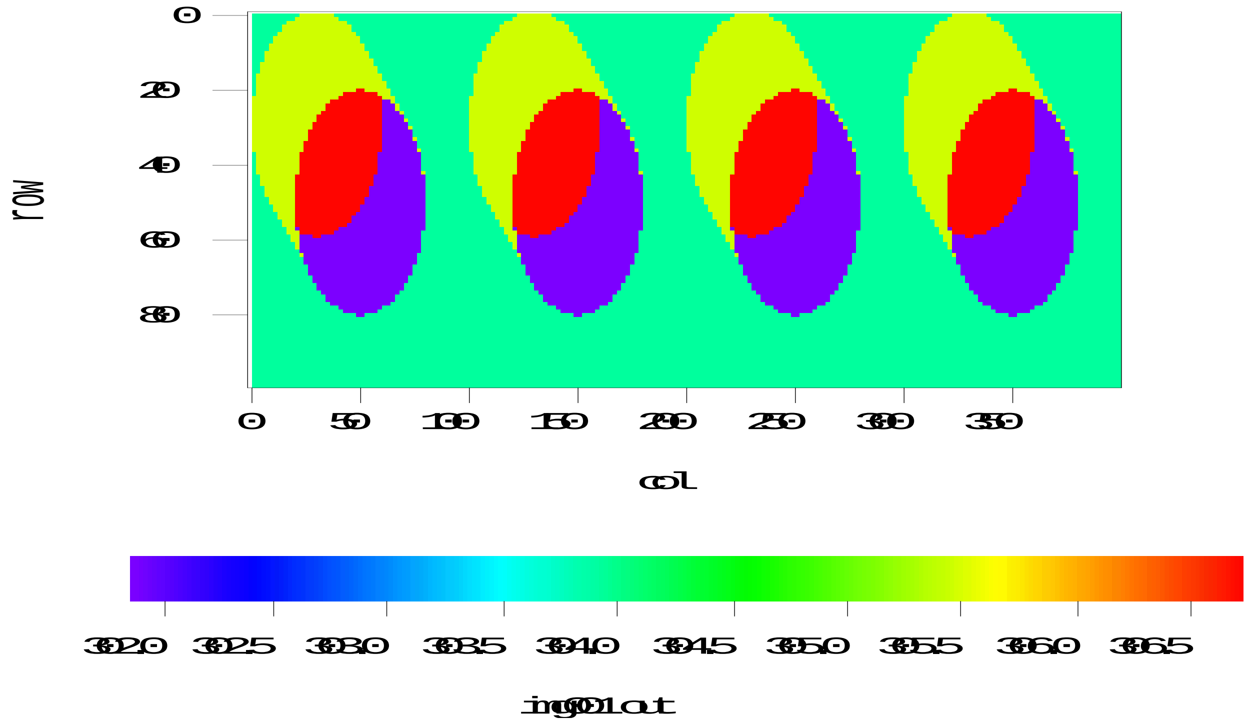


A.15 Cooling Tower Model Temperatures ('DIAG' and roi = 1)

The cooling tower model temperature Tecplot file is written to file CTModelTemps.plt. The graphics file shows the water deck temperature (cross-flow cooling tower), solid deck temperature, throat temperature, inner and outer fan shroud temperatures for each cooling tower in the simulation. The following picture illustrates these temperatures for a 4 cell bank of cooling towers.



A similar file is written to imgxxx.out (xxx is the image number) for importing into Noesys Transform. The image generated by Transform is

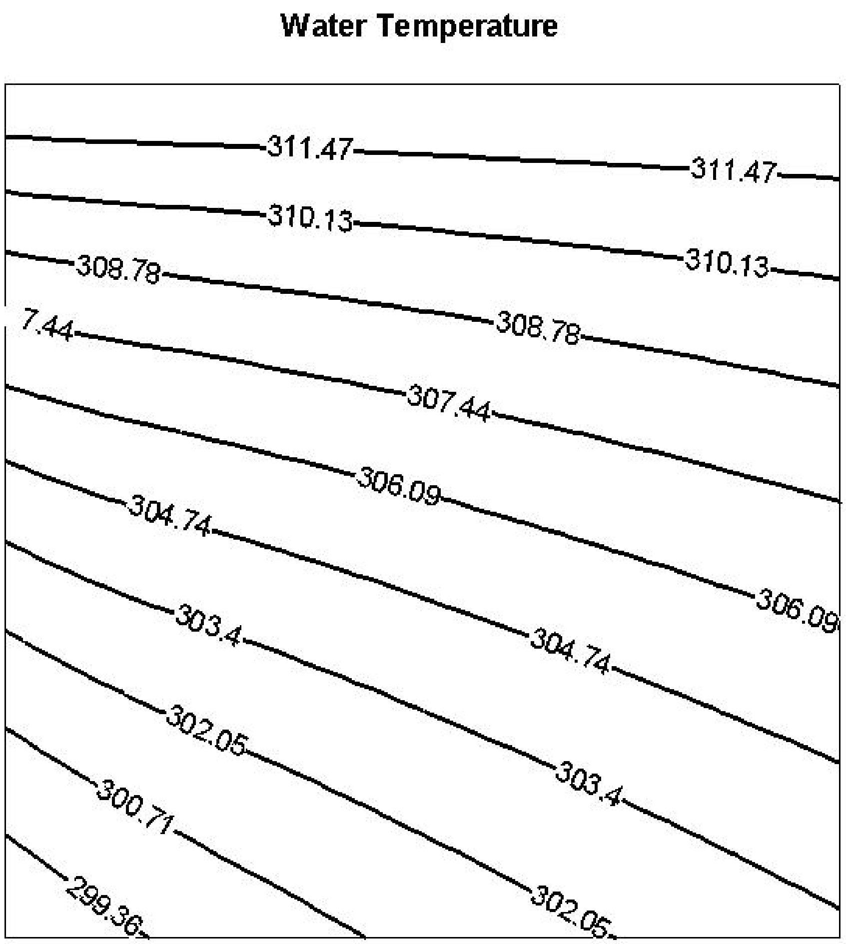


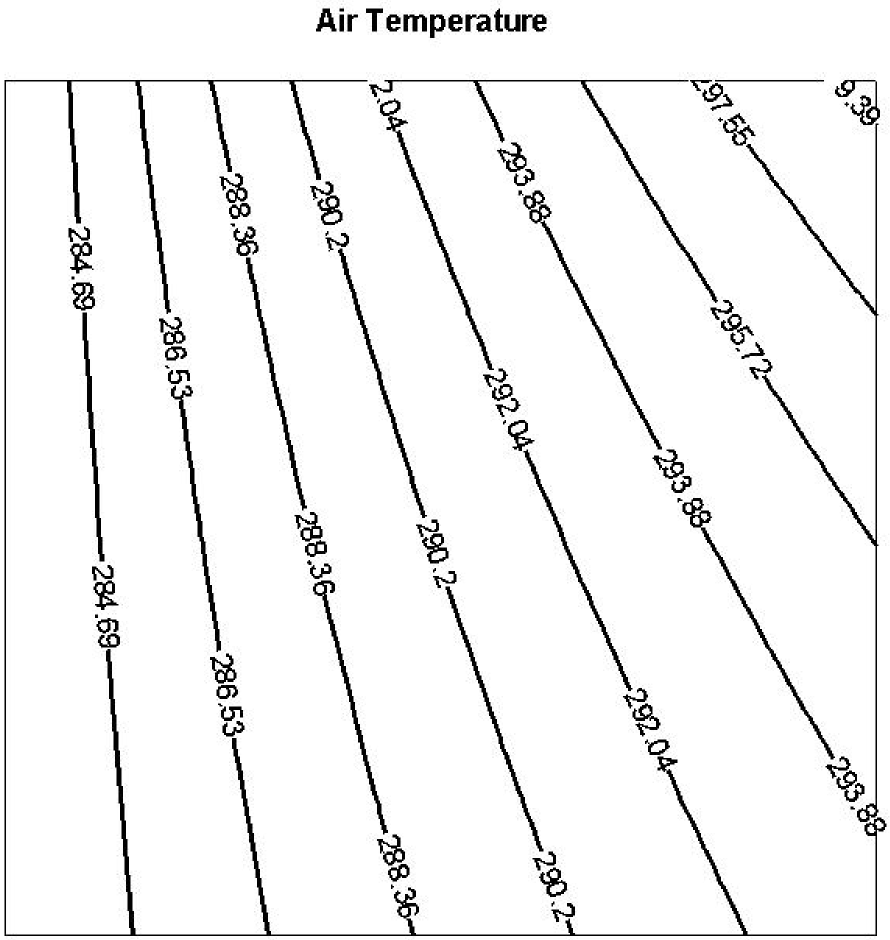
A summary of the deck ray tracing algorithm material area fractions used to compute area-averaged surface temperatures is written to raytracing.txt. An example of this file is:

```
Summary of Deck Ray Tracing Algorithm


  Mat  frac
  ---  ----
   1   0.00
   2   0.00
   3   0.54
   4   0.12
   5   0.17
   6   0.17


  Tot  1.00
```

A.16 Spatial Distributions of Cooling Tower Variables (‘DIAG’, ‘CFCT’ or XFCT’)

The spatial distribution of water temperature and water mass flux is written to Tecplot file Water-side.plt for counterflow cooling towers and to Water-side-1.plt and Water-side-2.plt for cross-flow cooling towers (2 fill sections). The spatial distribution of air temperature, humidity ratio, relative humidity and enthalpy is written to Air-side.plt for counterflow cooling towers and to Air-side-1.plt and Air-side-2.plt for cross-flow cooling towers. The Lewis factor spatial distribution is written to Le-side.plt for counter flow cooling towers and to Le-side-1.plt and Le-side-2.plt for cross-flow cooling towers. All the above mentioned plots are written for each image or observation. Here are some examples of the profiles in the fill section of a cross-flow cooling tower..




Air Temperature
284.69
286.53
288.36
290.2
292.04
293.88
295.72
297.55
284.69
286.53
288.36
290.2
292.04
293.88
288.36
290.2
292.04
293.88

Appendix B Governing Equations for the Fill Sections

The solution algorithms for the fill sections of counterflow and cross-flow cooling towers are herein described in detail. Air flowing through the cooling tower cools the water by both convection heat transfer and evaporative cooling at the air/water interface. The governing equations are: the liquid water and water vapor continuity equations, the first law of thermodynamics for both the water and air, and the relations for heat and mass transfer at the air/water interface. The flow regimes in the two types of cooling towers differ, and the solution algorithms are described separately.

Counterflow Cooling Tower

The fill section of a counterflow cooling tower is modeled as a set of parallel vertical flat plates. Water flows down the vertical surfaces of the plates as thin films, and air flows vertically upward through the channels formed by the parallel plates. The fill section is divided into a number of stacked horizontal slice control volumes. Figure B-1 shows a single control volume with a falling water film and the adjacent rising air stream. An outer computational loop solves the air/water concurrent or countercurrent continuity and energy equations iteratively for the mass flowrate of water, water temperature, air temperature and humidity ratio through the cooling tower. Newton's method is used to solve for the four variables within a fill section control volume. An additional mechanical energy equation is used to solve for the mass flowrate of air through the cooling tower during natural draft/wind-aided operation (fan off).

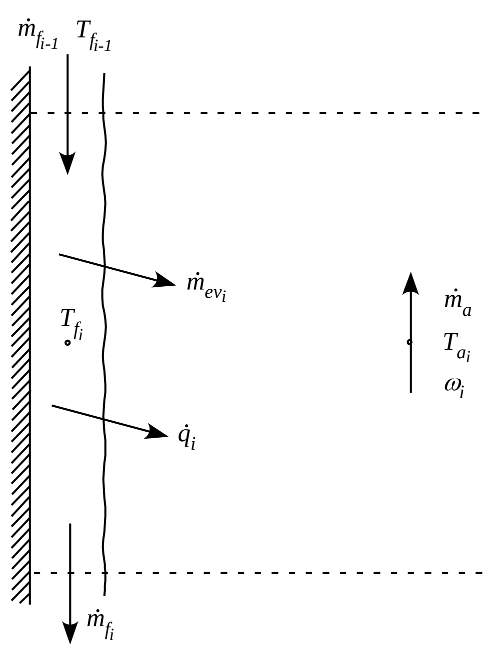


Figure B-1. Schematic of heat and mass transfer between the falling water film and the rising air stream in a horizontal slice control volume of the fill section of a counterflow cooling tower.

Equation B-1a and B-1b represent the evaporation rates for unsaturated and supersaturated air. The derivation of Eq. B-1 is given in Appendix C. The vapor pressure in Eq. B-1b is limited by the humidity ratio at saturation (Kloppers and Kroger, 2004).

$$\dot{m}_{ev_i} = \frac{k_m A_s M_{H_2O}}{\overline{R}} \left(\frac{P_{vs_i}}{T_{w_i}} - \frac{\omega_i P}{T_{a_i}(0.622 + \omega_i)} \right) \quad \text{(B-1a)}$$

$$\dot{m}_{ev_i} = \frac{k_m A_s M_{H_2O}}{\overline{R}} \left(\frac{P_{vs_i}}{T_{w_i}} - \frac{\omega_{s,i} P}{T_{a_i}(0.622 + \omega_{s,i})} \right) \quad \text{(B-1b)}$$

Equation B-2 is the liquid continuity equation for the falling film in a single control volume. The i-1 index represents inflow into the control volume and the i index corresponds to an outflow.

$$\dot{m}_{wi-1} - \dot{m}_{ev_i} = \dot{m}_{wi} \quad \text{(B-2)}$$

Equation B-3 is the air/water vapor energy balance equation. The first term in the equation is the change in flow enthalpy of the air/water vapor mixture. The second and third terms represent the mass and sensible heat transfer, respectively.

$$\dot{m}_a (C_{p,a_i}(T_{a_{i-1}} - T_{a_i}) + \omega_{i-1} h_{g,a_{i-1}} - \omega_i h_{g,a_i}) + (\dot{m}_{w_{i-1}} - \dot{m}_{w_i}) h_{g,w_i} = hA(T_{a_i} - T_{w_i}) \quad \text{(B-3)}$$

Equation B-4 is the liquid energy balance equation for the falling film. The LHS of the equation is the change in flow enthalpy of the falling film. The RHS of the equation is the mass and sensible heat transfer, respectively.

$$\dot{m}_{wi-1} h_{f,w_{i-1}} - \dot{m}_{wi} h_{f,w_i} = (\dot{m}_{w_{i-1}} - \dot{m}_{w_i}) h_{g,w_i} + hA(T_{w_i} - T_{a_i}) \quad \text{(B-4)}$$

Equation B-5 is the water vapor continuity equation. The RHS of the equation is the evaporation rate which translates into a change in the humidity ratio.

$$\dot{m}_a(\omega_i - \omega_{i-1}) = \dot{m}_{wi-1} - \dot{m}_{wi} \quad \text{(B-5)}$$

$i-1$ ....control volume inflow
i ....control volume outflow
$\dot{m}_w$ ....mass flowrate of water, kg/s
$\dot{m}_{ev}$ ....mass transfer rate from the falling film, kg/s
$\dot{m}_a$ ....mass flowrate of air, kg/s
$C_{p,a}$ ....specific heat of dry air, J/kg K
T_a ....air temperature, K
T_w ....water temperature, K
ω ....humidity ratio, kg water vapor/kg dry air
$h_{f,w}$ ....specific saturated liquid enthalpy at the water temperature, J/kg
$h_{g,a}$ ....specific saturated vapor enthalpy at the air temperature, J/kg
$h_{g,w}$ ....specific saturated vapor enthalpy at the water temperature, J/kg
h ....falling film heat transfer coefficient, W/m^2 K
A ....effective falling film surface area, m^2

The specific saturated liquid and vapor enthalpies for water are functions of the temperature, and over the temperature range 273 K ≤ T ≤ 323 K, the following linear relations apply:

$$h_f = a_{0f} + a_{1f} T_w \quad \begin{cases} a_{0f} = -1.143423776 \times 10^6 \\ a_{1f} = 4.18650768 \times 10^3 \end{cases} \tag{B-6}$$

$$h_g = a_{0g} + a_{1g} T_a \quad \begin{cases} a_{0g} = 2.00574399 \times 10^6 \\ a_{1g} = 1.815437 \times 10^3 \end{cases} \tag{B-7}$$

Equation B-2 through B-5 are four simultaneous non-linear equations which are solved for the effluent water film temperature, air temperature, mass flowrate of water and humidity ratio. The upstream (inflow) values of the variables are known. The convective heat transfer coefficient and the mass transfer coefficient are functions of the air flow Reynolds number. The Nusselt and Sherwood number correlations are listed in Appendix C. The four simultaneous equations are solved iteratively by Newton's method. Equation B-8 through B-11 represent four simultaneous equations arranged such that the RHS are equal to zero.

Equation B-12 is the matrix equation which is solved for the updates to the four variables. The matrix equation is solved by putting the Jacobian matrix in upper diagonal form and back substituting for the variable updates. The variables are then updated for the current Newton iteration using Eq. B-13. The "f" equations and the partial derivatives are updated with the new values of the variables and the procedure is repeated until the solution converges.

$$f_1 = \dot{m}_{wi-1} - \dot{m}_{ev_i} - \dot{m}_{wi} \tag{B-8}$$

$$\begin{aligned} f_2 = {} & \dot{m}_a (C_{p,a_i} (T_{a_{i-1}} - T_{a_i}) + \omega_{i-1} h_{g,a_{i-1}} - \omega_i h_{g,a_i}) \\ & + (\dot{m}_{w_{i-1}} - \dot{m}_{w_i}) h_{g,w_i} - hA(T_{a_i} - T_{w_i}) \end{aligned} \tag{B-9}$$

$$f_3 = \dot{m}_{wi-1} h_{f,w_{i-1}} - \dot{m}_{wi} h_{f,w_i} - (\dot{m}_{w_{i-1}} - \dot{m}_{w_i}) h_{g,w_i} - hA(T_{w_i} - T_{a_i}) \tag{B-10}$$

$$f_4 = \dot{m}_a (\omega_i - \omega_{i-1}) - (\dot{m}_{wi-1} - \dot{m}_{wi}) \tag{B-11}$$

$$\begin{bmatrix} \frac{\partial f_1}{\partial T_{w_i}} & \frac{\partial f_1}{\partial T_{a_i}} & \frac{\partial f_1}{\partial \dot{m}_{w_i}} & \frac{\partial f_1}{\partial \omega_i} \\ \frac{\partial f_2}{\partial T_{w_i}} & \frac{\partial f_2}{\partial T_{a_i}} & \frac{\partial f_2}{\partial \dot{m}_{w_i}} & \frac{\partial f_2}{\partial \omega_i} \\ \frac{\partial f_3}{\partial T_{w_i}} & \frac{\partial f_3}{\partial T_{a_i}} & \frac{\partial f_3}{\partial \dot{m}_{w_i}} & \frac{\partial f_3}{\partial \omega_i} \\ \frac{\partial f_4}{\partial T_{w_i}} & \frac{\partial f_4}{\partial T_{a_i}} & \frac{\partial f_4}{\partial \dot{m}_{w_i}} & \frac{\partial f_4}{\partial \omega_i} \end{bmatrix} \begin{Bmatrix} \Delta T_{w_i} \\ \Delta T_{a_i} \\ \Delta \dot{m}_{w_i} \\ \Delta \omega_i \end{Bmatrix} = - \begin{Bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{Bmatrix} \tag{B-12}$$

$$\begin{aligned} T_{w_i}^{n+1} &= T_{w_i}^{n} + \Delta T_{w_i} \\ T_{a_i}^{n+1} &= T_{a_i}^{n} + \Delta T_{a_i} \\ \dot{m}_{w_i}^{n+1} &= \dot{m}_{w_i}^{n} + \Delta \dot{m}_{w_i} \\ \omega_i^{n+1} &= \omega_i^{n} + \Delta \omega_i \end{aligned} \tag{B-13}$$

n ....previous Newton iteration
$n+1$ ....current Newton iteration

Cross-flow Cooling Tower

The flow in the fill section of a cross-flow cooling tower cannot be treated in a one-dimensional manner because the spatial distributions of air and water temperatures are necessarily two-dimensional. The water droplets cool as they drop vertically and the air heats-up as it flows horizontally into the cooling tower. The evaporation rate is not very sensitive to pressure, so momentum equations for the horizontal air flow and falling droplet flow are neglected. The air flow is assumed to be horizontal, parallel to the splash plates, and the water droplets are assumed to drop vertically as shown in Fig. B-2, a schematic of a single control volume in the fill section. The water droplets are assumed to be spherical and uniform in diameter. The droplet velocity and the droplet density are also assumed to be constant. The splash bars in the fill limit the distance a single drop can fall, see Fig. 4, and the droplet velocity is the mean velocity of a droplet, initially at rest, falling this distance. The mass flowrate of the droplets is a function of the liquid density, droplet density (droplets/m3), the droplet volume, the droplet surface area and the droplet velocity.

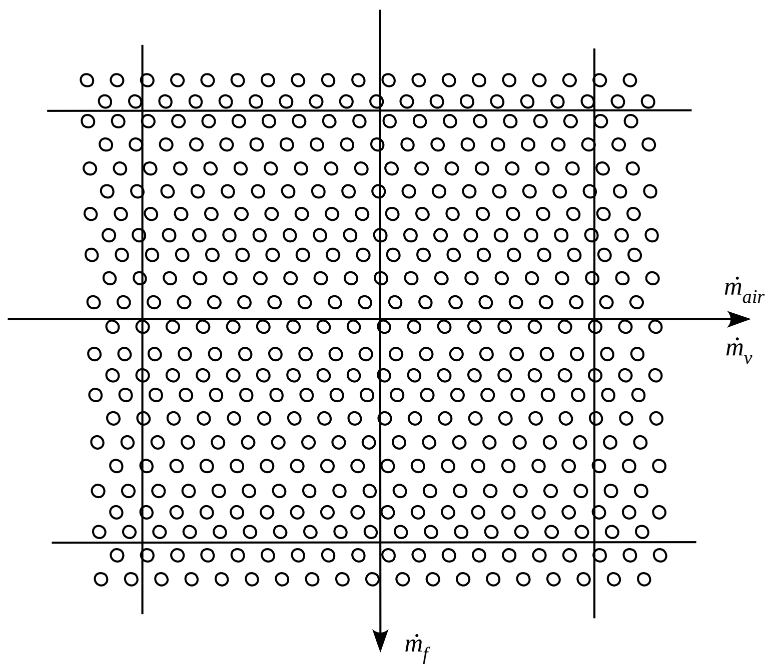


Figure B-2. Schematic of the flow in a single control volume of the fill section computational mesh.

Equation B-14a and B-14b are the expressions for the evaporation rate from the suspended water droplets in a control volume for unsaturated and supersaturated air. This quantity is derived in Appendix C.

$$\dot{m}_{ev_{i,j}} = \frac{\rho_d V k_m A_s M_{H_2O}}{\overline{R}} \left(\frac{P_{vs_{i,j}}}{T_{w_{i,j}}} - \frac{\omega_{i,j} P}{T_{a_{i,j}} (0.622 + \omega_{i,j})} \right) \qquad \text{(B-14a)}$$

$$\dot{m}_{ev_{i,j}} = \frac{\rho_d V k_m A_s M_{H_2O}}{\overline{R}} \left(\frac{P_{vs_{i,j}}}{T_{w_{i,j}}} - \frac{\omega_{s_{i,j}} P}{T_{a_{i,j}}(0.622 + \omega_{s_{i,j}})} \right) \tag{B-14b}$$

$$\rho_d = \frac{\dot{m}_f}{\rho_f V_d A_d v_d} \tag{B-15}$$

The four simultaneous non-linear equations that were solved for the counterflow cooling tower control volume are rewritten for the cross-flow cooling tower as

Equation B-20 is the matrix equation which is solved for the updates to the four variables. The matrix equation is solved by putting the Jacobian matrix in upper diagonal form and back substituting for the variable updates. The variables are then updated for the current Newton iteration using Eq. B-21. The "f" equations and the partial derivatives are updated with the new values of the variables and the procedure is repeated until the solution converges.

$$f_1 = \dot{m}_{w\,i,j-1} - \dot{m}_{ev_{ij}} - \dot{m}_{w\,i,j} \tag{B-16}$$

$$\begin{aligned} f_2 = {} & \dot{m}_a (C_{p,a_{i,j}} (T_{a_{i-1,j}} - T_{a_{i,j}}) + \omega_{i-1,j} h_{g,a_{i-1,j}} - \omega_{i,j} h_{g,a_{i,j}}) \\ & + (\dot{m}_{w_{i,j-1}} - \dot{m}_{w_{i,j}}) h_{g,w_{i,j}} - hA(T_{a_{i,j}} - T_{w_{i,j}}) \end{aligned} \tag{B-17}$$

$$f_3 = \dot{m}_{w\,i,j-1} h_{f,w_{i,j-1}} - \dot{m}_{w\,i,j} h_{f,w_{i,j}} - (\dot{m}_{w_{i,j-1}} - \dot{m}_{w_{i,j}}) h_{g,w_{i,j}} - hA(T_{w_{i,j}} - T_{a_{i,j}}) \tag{B-18}$$

$$f_4 = \dot{m}_a (\omega_{i,j} - \omega_{i-1,j}) - (\dot{m}_{w\,i,j-1} - \dot{m}_{w\,i,j}) \tag{B-19}$$

$$\begin{bmatrix} \frac{\partial f_1}{\partial T_{w_{i,j}}} & \frac{\partial f_1}{\partial T_{a_{i,j}}} & \frac{\partial f_1}{\partial \dot{m}_{w_{i,j}}} & \frac{\partial f_1}{\partial \omega_{i,j}} \\ \frac{\partial f_2}{\partial T_{w_{i,j}}} & \frac{\partial f_2}{\partial T_{a_{i,j}}} & \frac{\partial f_2}{\partial \dot{m}_{w_{i,j}}} & \frac{\partial f_2}{\partial \omega_{i,j}} \\ \frac{\partial f_3}{\partial T_{w_{i,j}}} & \frac{\partial f_3}{\partial T_{a_{i,j}}} & \frac{\partial f_3}{\partial \dot{m}_{w_{i,j}}} & \frac{\partial f_3}{\partial \omega_{i,j}} \\ \frac{\partial f_4}{\partial T_{w_{i,j}}} & \frac{\partial f_4}{\partial T_{a_{i,j}}} & \frac{\partial f_4}{\partial \dot{m}_{w_{i,j}}} & \frac{\partial f_4}{\partial \omega_{i,j}} \end{bmatrix} \begin{Bmatrix} \Delta T_{w_{i,j}} \\ \Delta T_{a_{i,j}} \\ \Delta \dot{m}_{w_{i,j}} \\ \Delta \omega_{i,j} \end{Bmatrix} = - \begin{Bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{Bmatrix} \tag{B-20}$$

$$\begin{aligned} T_{w_{i,j}}^{n+1} &= T_{w_{i,j}}^{n} + \Delta T_{w_{i,j}} \\ T_{a_{i,j}}^{n+1} &= T_{a_{i,j}}^{n} + \Delta T_{a_{i,j}} \\ \dot{m}_{w_{i,j}}^{n+1} &= \dot{m}_{w_{i,j}}^{n} + \Delta \dot{m}_{w_{i,j}} \\ \omega_{i,j}^{n+1} &= \omega_{i,j}^{n} + \Delta \omega_{i,j} \end{aligned} \tag{B-21}$$

$i-1$.................control volume inflow in horizontal direction
i ....control volume outflow in horizontal direction
$j-1$ ....control volume inflow in vertical direction

j ....control volume outflow in vertical direction

Appendix C Water/Air Heat and Mass Transfer

There are two distinct water flow regimes in cooling towers in which heat and mass transfer occurs between water and air, a falling film and falling drops. Figure C-1 shows both of these flow regimes schematically. At the air/water interface there is a thin saturation layer in which the air is saturated with water vapor. The molar flux of water vapor is proportional to the difference in water vapor molar concentrations in the thin interfacial saturation layer and the free stream air. The implicit critical assumption in Eq. C-1 is that of a low mass-transfer rate. The proportionality constant is the mass transfer coefficient, as shown in Eq. C-1. If the air/water vapor mixture is considered a mixture of ideal gasses, the molar concentration of water vapor is a function of the temperature and partial pressure, Eq. C-2, and the molar flux is proportional to the difference between the partial pressure to temperature ratios for the interfacial saturation layer and the free stream air, Eq. C-3. The molar flux is converted to mass flowrate with the product of the interfacial surface area and the water vapor molecular weight, Eq. C-4.

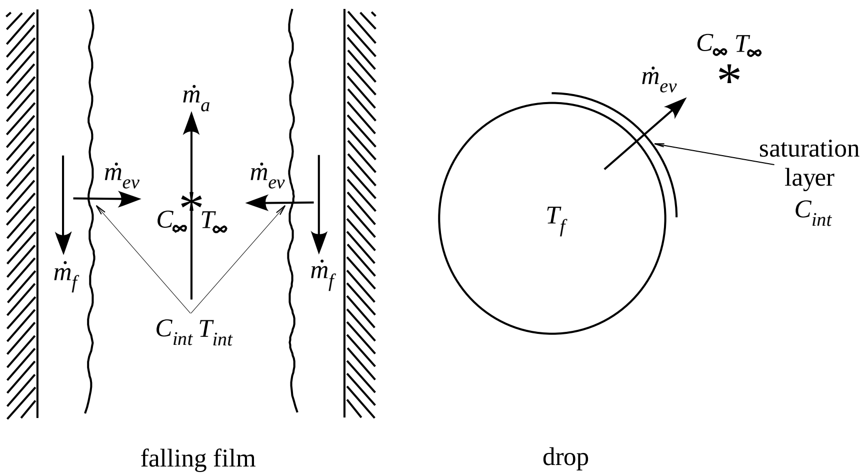


Figure C-1. Schematic of evaporation from a falling film and a water droplet.

$$N_{H_2O} = k_m\left(C_{int} - C_\infty\right) \tag{C-1}$$

$$C = \frac{n}{\bar{V}} = \frac{P}{\bar{R}T} \tag{C-2}$$

$$N_{H_2O} = \frac{k_m}{\bar{R}}\left(\frac{P_{int}}{T_{int}} - \frac{P_{v\infty}}{T_\infty}\right) \tag{C-3}$$

$$\dot{m}_{ev} = N_{H_2O}A_sM_{H_2O} = \frac{k_mA_sM_{H_2O}}{\bar{R}}\left(\frac{P_{int}}{T_{int}} - \frac{P_{v\infty}}{T_\infty}\right) \tag{C-4}$$

N_{H_2O} ....molar flux of water, mol/m^2s

k_m ....mass transfer coefficient, m/s

C ....interfacial or free stream molar concentration of water, mol/m^3

P ....saturation or partial pressure of water, Pa

T ....water or air temperature, K

A_s ....falling film interfacial surface area, m^2
M_{H_2O} ....molecular weight of water, g/g-mol
$\overline{R}$ ....universal gas constant, J/K-kmol
$\dot{m}_{ev}$ ....mass transfer rate from the falling film, kg/s

Equation C-5 is an expression for the saturation pressure of water vapor in SI units, and Eq. C-6 is an expression for the partial pressure of water vapor as a function of the humidity ratio. The temperature of the saturation layer is assumed to be the water temperature. Substitution of these two expressions into Eq. C-4 results in an expression for the evaporation rate, Eq. C-7, as a function of the water and air free stream temperatures, the pressure, and the humidity ratio. This expression is valid for both falling film and falling droplet flows. The value of the mass transfer coefficient is flow regime and geometry dependent.

$$P_{vs} = e^{a_0 + \frac{a_1}{T_w}} \begin{cases} a_0 = 25.5943 \\ a_1 = -5229.89 \end{cases} \tag{C-5}$$

$$P_v = \frac{\omega P}{0.622 + \omega} \tag{C-6}$$

$$\dot{m}_{ev} = \frac{k_m A_s M_{H_2O}}{\overline{R}} \left(\frac{P_{vs}}{T_w} - \frac{P_v}{T_a} \right) \tag{C-7}$$

If the interfacial area in Eq. C-7 is the surface area of a single droplet, then Eq. C-7 is the expression for the evaporation rate from a single droplet. The total evaporation rate for the suspended water droplets in a volume is the product of the single droplet evaporation rate and the number of droplets in the volume. The total number of droplets is a function of the droplet density. Equation C-8 is the expression for the evaporation rate from the suspended water droplets in a control volume. The droplet size is assumed to be uniform. The droplet density, Eq. C-9, is a function of the mass flowrate of water, the droplet velocity, and the droplet size.

$$\dot{m}_{ev} = \frac{\rho_d V k_m A_s M_{H_2O}}{\overline{R}} \left(\frac{P_{vs}}{T_w} - \frac{P_v}{T_a} \right) \tag{C-8}$$

$$\rho_d = \frac{\dot{m}_f}{\rho_f V_d A_d v_d} \tag{C-9}$$

ρ_d ....droplet density, # of droplets/m^3
$\dot{m}_f$ ....mass flowrate of water, kg/s
ρ_f ....density of water, kg/m^3
V ....fill or rain section volume, m^3
V_d ....droplet volume, m^3
A_d ....droplet surface area, m^2
v_d ....droplet velocity, m/s

The value of the mass transfer coefficient is determined with the Sherwood number in the same manner that the convective heat transfer coefficient is determined with the Nusselt number. Based on the analogy between heat and mass transfer, the Sherwood number is assumed to have the same functional relationship to the Reynolds number and the Schmidt number that the Nusselt number has to the Reynolds number and the Prandtl number. The definitions of the Sherwood and Schmidt numbers are shown in Eq. C-10. Equation C-11 is an expression for the binary mass diffusivity of air/water vapor, as a function of the absolute temperature, at atmospheric pressure

$$Sh_d = \frac{k_m d}{D_{av}} \quad \text{and} \quad Sc = \frac{\nu}{D_{av}} \tag{C-10}$$

$$D_{av} = \frac{7.06085\times10^{-9} T^{3/2}}{2.65322 - 0.0061681T + 6.55266\times10^{-6} T^2} \tag{C-11}$$

d ....droplet diameter, m
ν ....kinematic viscosity of air, m^2/s
D_{av} ....mass diffusivity of air/water vapor, m^2/s
T ....air temperature, K

The flow through the fill section of a counterflow cooling tower is modeled as flow between heated parallel flat plates. The expressions for the Nusselt number are shown in Eq. C-12. The Nusselt number is assumed to vary linearly in the transition region between the laminar and fully-turbulent values. Equation C-13 is the expression for the Sherwood number. The performance of complicated fill geometries, designed to enhance heat and mass transfer, can be approximated by increasing the interfacial surface area.

$$\begin{aligned} Nu_d &= 8.235 && Re_d < 2300 \\ Nu_d &= 0.00324987\,Re_d + 0.9902987 && 2300 \le Re_d \le 10000 \\ Nu_d &= 0.023\,Re_d^{0.8}\,Pr^{1/3} && Re_d > 10000 \end{aligned} \tag{C-12}$$

$$Sh_d = Nu_d \left(\frac{Sc}{Pr}\right)^{1/3} \tag{C-13}$$

The water droplets in the fill sections of a cross-flow cooling tower and the rain section (not modeled) of a counterflow cooling tower are assumed to be spherical. Equation C-14 and C-15 are relations for the Nusselt and Sherwood numbers respectively for flow over a sphere. The Nusselt number relation normally has a viscosity temperature correction term. For moderate temperature differences with a gas, it is reasonable to neglect the viscosity correction

$$Nu_d = 2 + \left(0.4\,Re_d^{1/2} + 0.06\,Re_d^{2/3}\right) Pr^{0.4} \tag{C-14}$$

$$Sh_d = 2 + \left(0.4\,Re_d^{1/2} + 0.06\,Re_d^{2/3}\right) Sc^{0.4} \tag{C-15}$$

Appendix D Natural Draft/Wind-aided Mode

The mass flowrate of air through the cooling tower is specified by the model in the mechanical draft mode of operation. When the fan is turned off, the flowrate of air through the cooling tower is unknown. The air mass flowrate will be a function of operating parameters such as water inlet temperature, water flowrate and ambient conditions. Buoyancy due to the hot water flow will induce air circulation through the cooling tower. Wind pressure at the air inlet to the cooling tower will also enhance air flow through the tower. The air flowrate is determined from the overall mechanical energy equation for the air flow. The air flow is assumed to be incompressible; with the approximation that density is a function of temperature in the body force term.

Counterflow Cooling Tower

Figure D-1 is a schematic of one-dimensional flow through a counterflow cooling tower. The steady-state mechanical energy equations are written for each of the three sequential sections of the cooling tower and then summed. Equation D-1 is the overall mechanical energy equation for flow through the cooling tower. The ambient pressure at the top of the shroud is a function of the height of the cooling tower, Eq. D-2. Equation D-3 is the mechanical energy equation in terms of the inlet air mass flowrate. The equation is setup to allow for concurrent or countercurrent air flow. The change in flowrate due to evaporation is neglected, and the flow through the fill is assumed to be laminar.

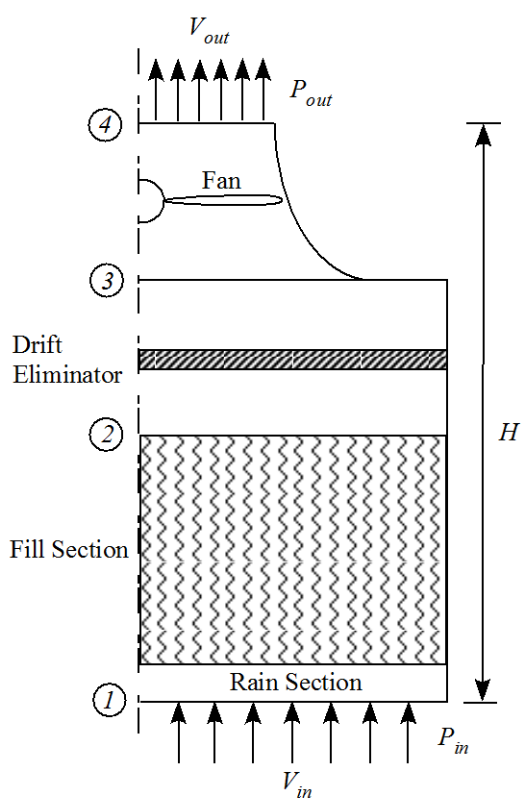


Figure D-1. Schematic of natural draft/wind-aided flow through a counterflow cooling tower.

$$p_{in} + \rho \frac{V_{in}^2}{2} = p_{out} + \rho \frac{V_{out}^2}{2} + \sum_{fill+rain} \overline{\rho} g \Delta z + \overline{\rho} g (z_4 - z_2) + \rho \left(K_{fill} + \frac{fL}{D} \right) \frac{V_{fill}^2}{2} + \rho K_{2-3} \frac{V_{2-3}^2}{2} + \rho K_{3-4} \frac{V_{3-4}^2}{2} \qquad \text{(D-1)}$$

$$p_{out} = p_{in} - \rho g H - \rho \frac{V_w^2}{2} \qquad \text{(D-2)}$$

$$f = \frac{1}{2\rho} \left(\frac{1}{A_{out}^2} - \frac{1}{A_{in}^2} + \frac{K_{fill}}{A_{fill}^2} + \frac{96}{Re} \frac{L_{fill}}{D_h A_{fill}^2} + \frac{K_{2-3}}{A_{2-3}^2} + \frac{K_{3-4}}{A_{3-4}^2} \right) |\dot{m}_a| \dot{m}_a + \sum_{fill+rain} \overline{\rho} g \Delta z + \overline{\rho} g (z_4 - z_2) - \rho g H - \rho \frac{V_w^2}{2} \qquad \text{(D-3)}$$

p_{in} ....cooling tower inlet pressure, Pa
p_{out} ....cooling tower outlet pressure, Pa
ρ ....ambient air density, kg/m^3
$\overline{\rho}$ ....air density evaluated at the local air temperature within the tower, kg/m^3
V_{in} ....cooling tower inlet air velocity, m/s
V_{out} ....cooling tower outlet air velocity, m/s
V_w ....wind speed at cooling tower inlet, m/s
g ....acceleration due to gravity, m/s^2
z ....cooling tower elevations, m
Δz ....fill or rain section cell size, m
H ....height from bottom of rain section to top of fan shroud, m
L_{fill} ....fill section height + drift eliminator thickness, m
D_h ....hydraulic diameter of fill section, m
A_{in} ....inlet or rain section flow area, m^2
A_{out} ....outlet or fan shroud exit flow area, m^2
K ....form losses for various sections within cooling tower
Re ....fill section Reynold's number, $V_{fill} D_h / \nu$
$\dot{m}_a$ ....mass flowrate of dry air,kg/s

Equation D-3 is solved iteratively for the air mass flowrate by Newton's method, Eq. D-4 and D-5. The friction factor in Eq. D-3 is a function of the mass flowrate of dry air, so the partial derivative term is evaluated numerically.

$$\frac{\partial f}{\partial \dot{m}_a} = \frac{f(\dot{m}_a + \delta \dot{m}_a)}{\delta \dot{m}_a} \rightarrow \Delta \dot{m}_a = \frac{-f}{\partial f / \partial \dot{m}_a} \qquad \text{(D-4)}$$

$$\dot{m}_a^{n+1} = \dot{m}_a^n + \Delta \dot{m}_a \qquad \text{(D-5)}$$

Cross-flow Cooling Tower

With the fan shut-off, air will flow through the cooling tower due to buoyancy and wind pressure in the center region. Figure D-2 is a schematic of natural draft/wind-aided flow through a cross-flow cooling tower. Wind will stagnate on the windward side of the cooling tower, increasing the pressure on the vertical face. Because air enters the cooling tower through almost the entire vertical face, natural draft flow through cross-flow cooling towers is sensitive to wind. Equation D-6 shows the mechanical energy equation for the flows through the two sides of the cooling tower. p_1 is the pressure on the windward side of the cooling tower, and p_2 is the pressure on the leeward side, assumed to be atmospheric. The stagnation pressure is calculated from the component of wind velocity normal to the windward side of the cooling tower. The effect of wind is to increase flow through the windward side of the cooling tower and decrease flow through the leeward side.

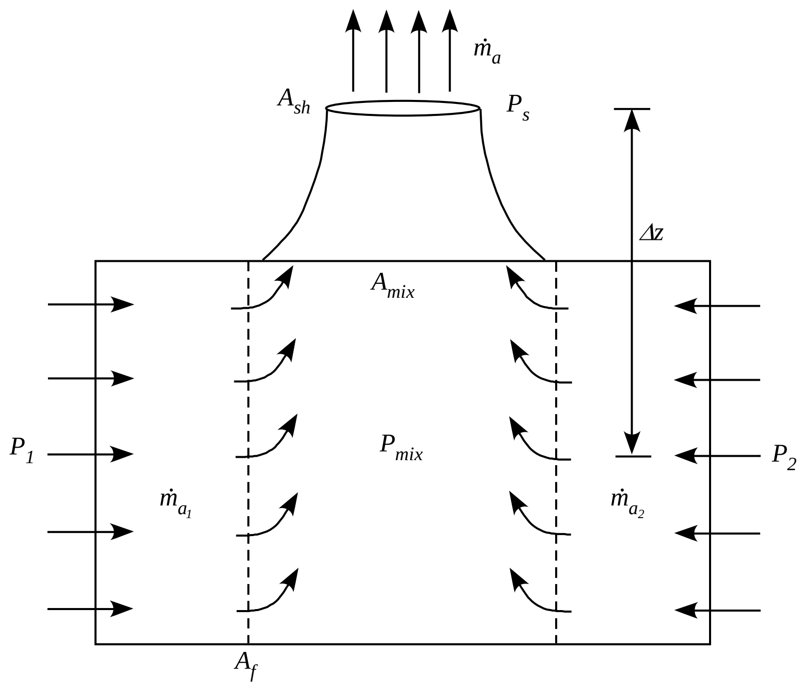


Figure D-2. Schematic of natural draft/wind-aided flow through a cross-flow cooling tower.

$$p_1 = p_{mix} + (1 + K_f)\frac{\dot{m}_{a1}^2}{2\rho A_f^2} = p_{atm} + \rho\frac{V_w^2}{2}$$
$$p_2 = p_{mix} + (1 + K_f)\frac{\dot{m}_{a2}^2}{2\rho A_f^2} = p_{atm} \qquad \text{(D-6)}$$

p_1 ....pressure on the windward side, Pa
p_2 ....pressure on the leeward side, Pa
p_{mix} ....mixture pressure in the center of the tower, Pa
p_{atm} ....atmospheric pressure, Pa
K_f ....fill section form loss, -

A_f ....fill section horizontal flow area, m^2

$\dot{m}_{a_1}$ ....mass flowrate of air through windward side, kg/s

$\dot{m}_{a_2}$ ....mass flowrate of air through leeward side, kg/s

The frictional and form losses will be due primarily to the dry air flowrate. The two relations in Eq. D-6 can be combined to eliminate the mixture pressure term, Eq. D-7.

$$p_1 - (1 + K_f)\frac{\dot{m}_{a_1}^2}{2\rho A_f^2} = p_2 - (1 + K_f)\frac{\dot{m}_{a_2}^2}{2\rho A_f^2} \quad \text{(D-7)}$$

The total mass flowrate of dry air is the sum of the mass flowrates of dry air through the two sides. Equation D-8 can be utilized to obtain two relations for the flowrates of dry air through the two sides of the cooling tower as functions of the pressure difference between the windward and leeward sides, Eq. D-9. Note that the impact of wind of the flow split between the two sides of the cooling tower is to decrease the flow in the leeward side by the same amount that it increases in the windward side.

$$\begin{aligned} \dot{m}_{a_1} &= \frac{\dot{m}_a}{2} + \frac{\rho A_f^2}{(1 + K_f)\dot{m}_a}(p_1 - p_2) \\ \dot{m}_{a_2} &= \frac{\dot{m}_a}{2} - \frac{\rho A_f^2}{(1 + K_f)\dot{m}_a}(p_1 - p_2) \end{aligned} \quad \text{(D-8)}$$

Equation D-9 is the mechanical energy equation for the vertical flow in the central region of the cooling tower.

$$p_{mix} + \frac{\dot{m}_a^2}{2\rho A_{mix}^2} = p_s + (1 + K_{sh})\frac{\dot{m}_a^2}{2\rho A_{sh}^2} + \rho_{mix} g \Delta z \quad \text{(D-9)}$$

p_s ....fan shroud exit pressure, Pa

ρ_{mix} ....mixture air density, kg/m3

Δz ....effective length of hot leg within cooling tower, m

K_{sh} ....fan shroud form loss, -

A_{sh} ....fan shroud exit flow area, -

The pressure on the leeward side of the cooling tower is assumed to be the ambient pressure. Equation D-10 is the relation for the hydrostatic pressure at the top of the shroud. Equation D-11 is the relation for the mixture pressure as a function of the leeward pressure and the mass flowrate of dry air through the leeward side fill section. These two relations are substituted into Eq. D-9 and the result is a fourth order algebraic equation for the total mass flowrate of dry air through the cooling tower, Eq. D-12. Equation D-12 is solved iteratively for the air mass flowrate by Newton's method in the same manner as Eq. D-3 for the counterflow cooling tower natural draft/wind-aided air flowrate.

$$p_s = p_2 - \rho g \Delta z \quad \text{(D-10)}$$

$$p_{mix} = p_2 - \frac{(1+K_f)}{2\rho A_f^2}\left[\frac{\dot{m}_a}{2} - \frac{\rho A_f^2}{(1+K_f)\dot{m}_a}(p_1 - p_2)\right]^2 \tag{D-11}$$

$$f = \left[\frac{1+K_{sh}}{2\rho A_{sh}^2} + \frac{1+K_f}{8\rho A_f^2} - \frac{1}{2\rho A_{mix}^2}\right]\dot{m}_a^4 - \left[\frac{p_1 - p_2}{2} + (\rho - \rho_{mix})g\Delta z\right]\dot{m}_a^2 + \frac{\rho A_f^2}{2(1+K_f)}(p_1 - p_2)^2 \tag{D-12}$$

If the pressure difference between the two sides is large enough, the flowrate through the leeward side of the cooling tower, from Eq. D-8, will be negative. The numerical scheme for evaluating flow through the fill section is not valid for negative flowrates, therefore when the predicted flowrate through the leeward side of the cooling tower is negative; the flowrate is set to be zero. Figure D-3 is a schematic of natural convection through a cross-flow cooling tower in which the flow through one side is stagnant. Equation D-13 is the mechanical energy equation for flow through the fill section on the windward side, and Eq. D-14 is the mechanical energy equation for upward flow through the central region of the cooling tower. Equation D-15 is the shroud pressure as a function of the ambient pressure and the height of the cooling tower. Equation D-13 through D-15 can be combined to obtain a quadratic equation for the mass flowrate of dry air, Eq. D-16. This equation is solved iteratively by Newton's method.

$$p_1 = p_{mix} + \frac{(1+K_f)}{2\rho A_f^2}\dot{m}_a^2 \tag{D-13}$$

$$p_{mix} + \frac{\dot{m}_a^2}{2\rho A_{mix}^2} = p_s + (1+K_{sh})\frac{\dot{m}_a^2}{2\rho A_{sh}^2} + \rho_{mix} g\Delta z \tag{D-14}$$

$$p_s = p_{atm} - \rho g\Delta z \tag{D-15}$$

$$f = \left[\frac{1+K_{sh}}{2\rho A_{sh}^2} + \frac{1+K_f}{2\rho A_f^2} + \frac{1}{2\rho A_{mix}^2}\right]\dot{m}_a^2 - \left[(p_1 - p_{atm}) + (\rho - \rho_{mix})g\Delta z\right] \tag{D-16}$$

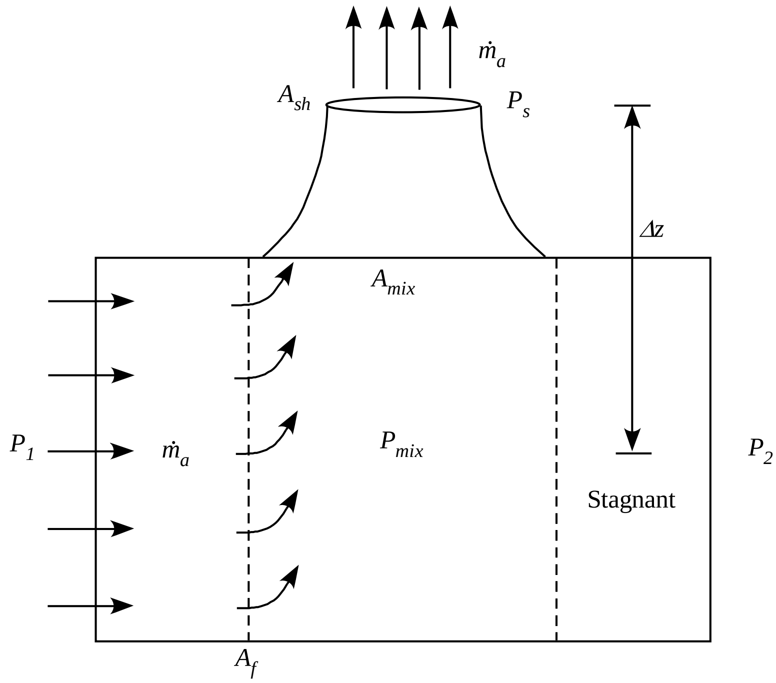


Figure D-3. Schematic of natural draft/wind-aided flow through a cross-flow cooling tower with stagnated flow in the leeward side.

Appendix E Calculation of Cross-Flow Fill Droplet Velocity and Hydraulic Loss Coefficient

The values of the hydraulic loss coefficient and the average droplet velocity are input parameters for the cooling tower model and are strongly dependent on the specific geometry of the fill section. They must be calculated separately for input into the model for a specific cooling tower. The procedure for determining the input parameters is herein described.

The fill sections in the SRS A-Area cooling tower consist of plastic splash plates that are four inches wide and perforated with arrays of ¼ inch holes. Figure E-1 shows the arrangement of the splash plates in the fill section. The horizontal spacing between adjacent splash plates is four inches and the vertical spacing between horizontal rows is eight inches. The splash plates in a horizontal row are offset with respect to the plates in the adjacent rows above and below, such that the maximum unobstructed vertical distance a droplet can fall is twice the spacing between rows, sixteen inches. The vertical velocity of the falling water droplets is assumed to be constant in the model, so for the average velocity of a water droplet the distance Δz is used. Because of air resistance, this velocity is a function of the droplet size.

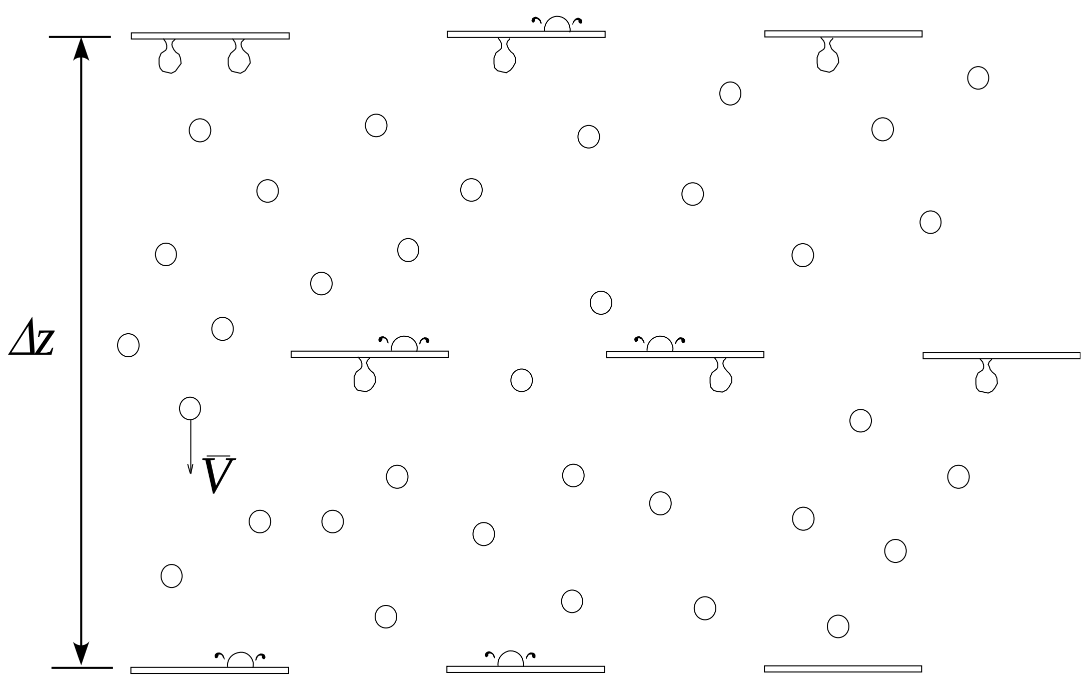


Figure E-1. Schematic of splash plates in a cross-flow cooling tower fill, showing the maximum unimpeded distance that a water droplet can fall.

The water drops in the fill section are assumed to be spherical, rigid, and of uniform diameter. Figure E-2 is a schematic of a falling sphere showing the gravitational and drag forces acting on it. Equation E-1 is Newton's second law for the sphere, and Eq. E-2 is the expression for the drag force due to external flow over a solid body. The drag is a function of the drag coefficient and the square of the free stream velocity. Equation E-3 is the resultant equation of motion for the falling water drop.

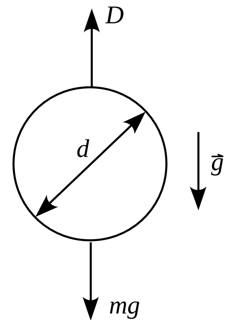


Figure E-2. Free falling water droplet.

$$m\frac{dV}{dt} = mg - D, \quad m = \frac{\rho_w \pi d^3}{6} \tag{E-1}$$

$$D = \tfrac{1}{2}\rho_a A C_D V^2, \quad A = \frac{\pi d^2}{4} \tag{E-2}$$

$$\frac{dV}{dt} = g - \frac{3}{4}\frac{\rho_a C_D}{\rho_w d}V^2 \tag{E-3}$$

The average velocity of the falling water droplet is the quotient of the distance Δz and the elapsed time required to travel the distance. The elapsed time for the droplet to fall Δz must be evaluated with Eq. E-3. Equation E-4 is an expression for the drag coefficient for steady flow past a sphere, as a function of the Reynolds number, and Fig. E-3 is a plot of the drag coefficient over the Reynolds number range of interest. While the drag coefficient at low Reynolds numbers can be very large, the drag force is small because of the low velocity. The drag coefficient is approximately inversely proportional to the velocity, while the drag force is proportional to the product of the drag coefficient and the square of the velocity. The drag force increases monotonically with increasing Reynolds number or velocity. The falling water droplet is assumed to start from rest, and early in the fall the drag force is negligible. At Reynolds numbers greater than 100, the drag coefficient decreases slowly with increasing Reynolds number. It is reasonable to assume a constant value for the drag coefficient in Eq. E-3. This allows an analytic solution to be obtained for the elapsed time for a falling droplet.

$$C_D = \frac{24}{Re_d} + \frac{6}{1+\sqrt{Re_d}} + 0.4 \tag{E-4}$$

Equation E-3 is a first-order non-linear differential equation. Using the definition of velocity, the independent variable t can be transformed to z and the differential equation will be linear for the dependent variable V^2, Eq. E-5.

$$\frac{dV^2}{dz} = 2g - \frac{3}{2}\frac{\rho_a C_D}{\rho_w d}V^2 \quad z = 0, V^2 = 0 \tag{E-5}$$

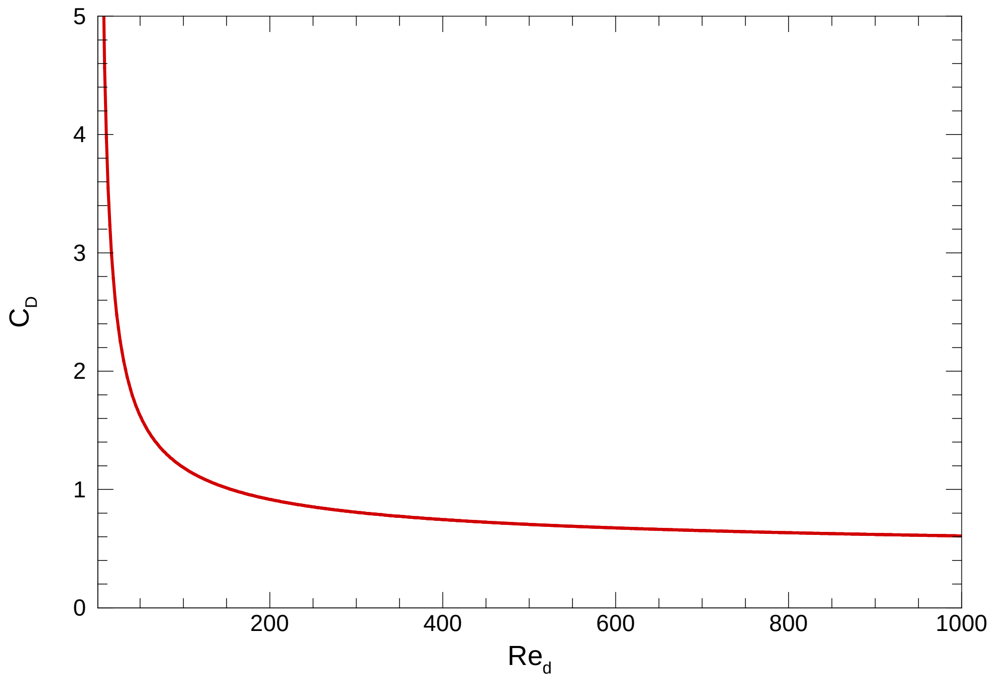


Figure E-3. Drag coefficient as a function of Reynolds number for flow past a sphere.

A general first-order ordinary differential equation has the following solution:

$$\frac{dy}{dx} + P(x)y = q(x), \quad y = \frac{\int u(x)q(x)dx + C}{u(x)}, \quad u(x) = e^{\int P(x)dx} \tag{E-6}$$

Equation E-7 is the solution of Eq. E-5. This is an expression for velocity as a function of distance fallen.

$$V = \sqrt{\frac{4\rho_w dg}{3\rho_a C_D}\left(1 - e^{-\frac{3}{2}\frac{\rho_a C_D}{\rho_w d}z}\right)} \tag{E-7}$$

With a change of variable, Eq. E-3 can be transformed into a form where separation of variables can be applied. An expression for elapsed time as a function of drop velocity can be obtained. Equation E-8 is a simplified form of Eq. E-3. Apply the following change of variable to obtain a separable non-linear differential equation, Eq. E-9.

$$\frac{dV}{dt} + \alpha V^2 - g = 0 \quad \text{where} \quad \alpha = \frac{3\rho_a C_D}{4\rho_w d} \tag{E-8}$$

Performing a change of variable

$$\eta = \alpha V^2 - g, \quad V^2 = \frac{\eta + g}{\alpha}, \quad dV = \frac{d\eta}{2\alpha V}$$

$$\frac{1}{2\alpha\sqrt{\dfrac{\eta+g}{\alpha}}}\frac{d\eta}{dt}+\eta=0, \quad \frac{d\eta}{\eta\sqrt{\alpha(\eta+g)}}=-2dt \tag{E-9}$$

This equation can be integrated directly to obtain an expression for η as a function of t, Eq. E-10.

$$\int\frac{dx}{x\sqrt{a+bx}}=\frac{-2}{\sqrt{a}}\tanh^{-1}\sqrt{\frac{a+bx}{a}}\rightarrow\frac{-2}{\sqrt{\alpha g}}\tanh^{-1}\sqrt{\frac{g+\eta}{g}}=-2t+C \tag{E-10}$$

The transformed initial condition is used to evaluate the constant of integration.

$$@\,t=0 \quad \begin{cases} V=0 \\ \eta=-g \end{cases} \rightarrow \quad C=0$$

Equation E-11 is the expression for elapsed time as a function of velocity

$$t=\frac{1}{\sqrt{\dfrac{3\rho_a C_D g}{4\rho_w d}}}\tanh^{-1}\left(V\sqrt{\frac{3\rho_a C_D}{4\rho_w d}}\right) \tag{E-11}$$

Substituting Eq. E-7 into Eq. E-11 results in an expression, Eq. E-12, for the elapsed time as a function of fall distance for a water drop,. As stated earlier, the average velocity is the quotient of the distance Δz and the elapsed time Δt.

$$\Delta t=\sqrt{\frac{4\rho_w d}{3\rho_a C_D g}}\tanh^{-1}\left(1-e^{-\frac{3}{2}\frac{\rho_a C_D}{\rho_w d}\Delta z}\right)^{1/2} \tag{E-12}$$

In the event the air is rising rather than still, the motion of a falling drop is more conveniently determined numerically. Equation E-13 is solved numerically for the new time velocity by forward differencing the time term and evaluating the RHS using the old time values. Equation E-14 is used to compute the average droplet velocity as a function of time. The numerator in Eq. E-14 is the fall distance as a function of time. Figure E-4 shows the average drop velocity in still air as a function of the fall distance for several drop diameters.

$$\frac{dV}{dt}=g-\frac{3}{4}\frac{\rho_a C_D}{\rho_w d}(V+V_{air})^2 \tag{E-13}$$

$$C_D=\frac{24}{Re_d}+\frac{6}{1+\sqrt{Re_d}}+0.4 \quad \text{and} \quad Re_d=\frac{\rho_a(V+V_{air})d}{\mu_{air}}$$

$$\overline{V}^n=\frac{\sum_1^n\left(\dfrac{V^{i-1}+V^i}{2}\right)\Delta t^i}{\sum_1^n \Delta t^i} \tag{E-14}$$

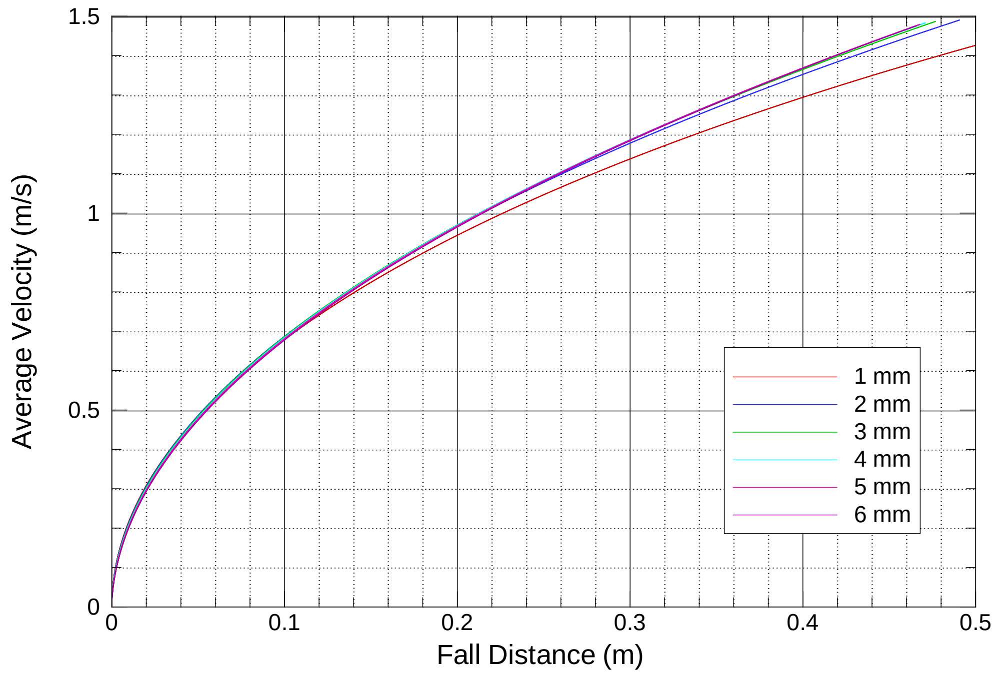


Figure E-4. Average free fall velocity of a spherical water droplet as functions of the droplet diameter and fall distance

The average velocity of a 4.0 mm water drop falling sixteen inches (0.4064 m) through still air is calculated to be 1.3954 m/s. With an assumed value for the drag coefficient of 0.75, Eq. E-12 gives a value of 0.29113 s for the elapsed time, and this gives a value of 1.3959 m/s for the average fall velocity.

The irreversible pressure drop of the horizontal air flow in the fill section of a cross-flow cooling tower is due to two phenomena: drag due to flow past the water drops, and wall shear from flow parallel to the splash bars. After flowing through the fill, the horizontal air flow passes through the drift eliminator, incurring further losses. The irreversible loss coefficient for the fill is important in evaluating the natural draft circulation through the cooling tower, and the value can be estimated.

The natural draft flow through one side of the SRS A-Area cooling tower is approximately 15 kg/s with a the flow area of 58.9 m^2, see Fig. E-5. The air velocity is approximately 0.2 m/s. Equation E-15 is the Reynolds number for flow past a spherical droplet with a diameter of 4.0 mm, and Eq. E-16 is the drag coefficient. Equation E-17 gives the drag on a single droplet.

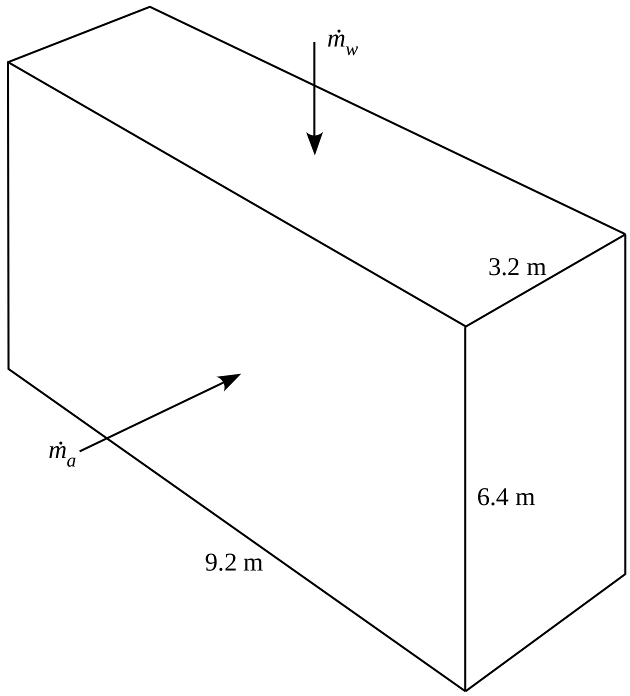


Figure E-5. Geometry of one of the fill sections of the SRS A-Area cross-flow cooling tower.

$$Re_d = \frac{\rho_a V d}{\mu} = \frac{1.1774(0.2)(0.004)}{1.983\times10^{-5}} = 47.5 \quad \text{(E-15)}$$

$$C_D = \frac{24}{Re_d} + \frac{6}{1+\sqrt{Re_d}} + 0.4 = \frac{24}{47.5} + \frac{6}{1+\sqrt{47.5}} + 0.4 = 1.67 \quad \text{(E-16)}$$

$$D = \frac{\pi}{8}\rho_a C_D V^2 d^2 = \frac{\pi}{8}(1.1774)(1.67)(0.2)^2(0.004)^2 = 4.942\times10^{-7}\,\text{N} \quad \text{(E-17)}$$

The mass flowrate of water flowing through each side of the SRS A-Area cooling tower is 30.98 kg/s, and the average droplet velocity is assumed to be 1.396 m/s. The droplet density in the fill is given by Eq. E-18. The total number of water droplets is the product of the droplet density and the fill volume, 4,246,897 droplets. The total drag force on the droplets and consequently the opposing force that the droplets exert on the air flow is the product of the number of droplets and the single droplet drag, Eq. E-19. The pressure drop due to flow past the droplets is the quotient of the drag and the air flow area, Eq. E-20. The value of the form loss coefficient for this pressure drop is evaluated in Eq. E-21.

$$\rho_d = \frac{\dot{m}_f}{\rho_f A V_d v_d} = \frac{30.98}{998(3.2)(9.2)(3.35\times10^{-8})1.396} = 2.255\times10^4 \,\text{dps}/\text{m}^3 \quad \text{(E-18)}$$

$$D_{tot} = 4{,}246{,}897(4.942\times10^{-7}) = 2.099\,\text{N} \quad \text{(E-19)}$$

$$\Delta P_{drops} = \frac{D_{tot}}{A} = \frac{2.099}{6.4(9.2)} = 0.0356\,\text{Pa} \quad \text{(E-20)}$$

$$K_{drops} = \frac{2\Delta P_{drops}}{\rho_a V^2} = \frac{2(0.0356)}{1.1774(0.2)^2} = 1.51 \quad \text{(E-21)}$$

There is also pressure drop due to flow past the splash plates. Figure E-6 shows the arrangement of the splash plates and the air flow area associated with each one. Each splash plate is centered in a square with 0.203 m sides. The number of splash plates in the fill is the quotient of the flow area and the area associated with each splash plate, Eq. E-22. The wetted perimeter of each splash plate is approximately twice the width or 0.203 m. The total wetted perimeter is the product of the splash plate wetted perimeter and the number of splash plates plus the enclosure perimeter, Eq. E-23. Equation E-24 is the calculation of the hydraulic diameter for the air flow through the fill. The Reynolds number based on the hydraulic diameter and an air velocity of 0.2 m/s is 8704. The smooth pipe friction factor from the Moody diagram is 0.031. The pressure drop is calculated with Eq. E-25, and the form loss coefficient is calculated in Eq. E-26. The value of the form loss coefficient for the fill is the sum of the two constituent form losses. In addition to the fill, there is an irreversible loss due to flow through the drift eliminator. The thickness of the drift eliminator is approximately six inches. It maneuvers the air flow such that entrained water droplets will impinge on the passage walls and be removed from the flow. The precise geometry of the drift eliminator is unknown, and therefore a value for a loss coefficient cannot be calculated but only estimated. It is expected that the eliminator pressure drop would be less than the fill pressure drop. The loss coefficient, kfil, in the input file for the fill section of cross-flow cooling towers includes the eliminator losses.

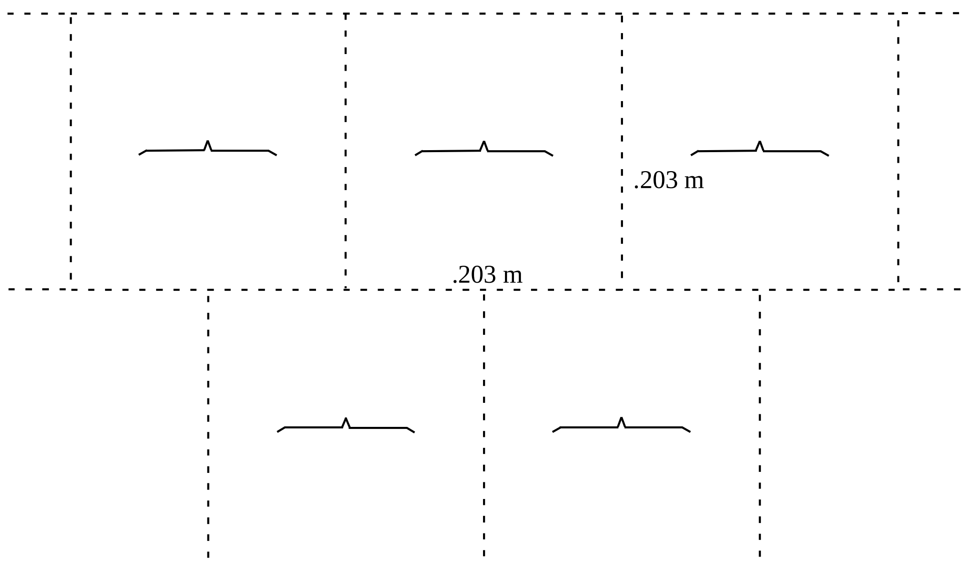


Figure E-6. Schematic of the fill showing the area associated with each splash plate.

$$\#\text{ of splash plates} = \frac{A_{tot}}{A_{SP}} = \frac{6.4(9.2)}{(.203)^2} = 1429 \quad \text{(E-22)}$$

$$P_w = 1429(0.203) + 2(6.4 + 9.2) = 321.29\,\text{m} \quad \text{(E-23)}$$

$$D_h = \frac{4A}{P_w} = \frac{4(6.4)(9.2)}{321.29} = 0.733\,\text{m} \quad \text{(E-24)}$$

$$\Delta P_{SP} = \frac{\rho f L}{D_h}\frac{V^2}{2} = \frac{1.1774(0.031)(3.2)(0.2)^2}{2(0.733)} = 0.00319\,\text{Pa} \tag{E-25}$$

$$K_{SP} = \frac{2\Delta P_{SP}}{\rho_a V^2} = \frac{2(0.00319)}{1.1774(0.2)^2} = 0.135 \tag{E-26}$$