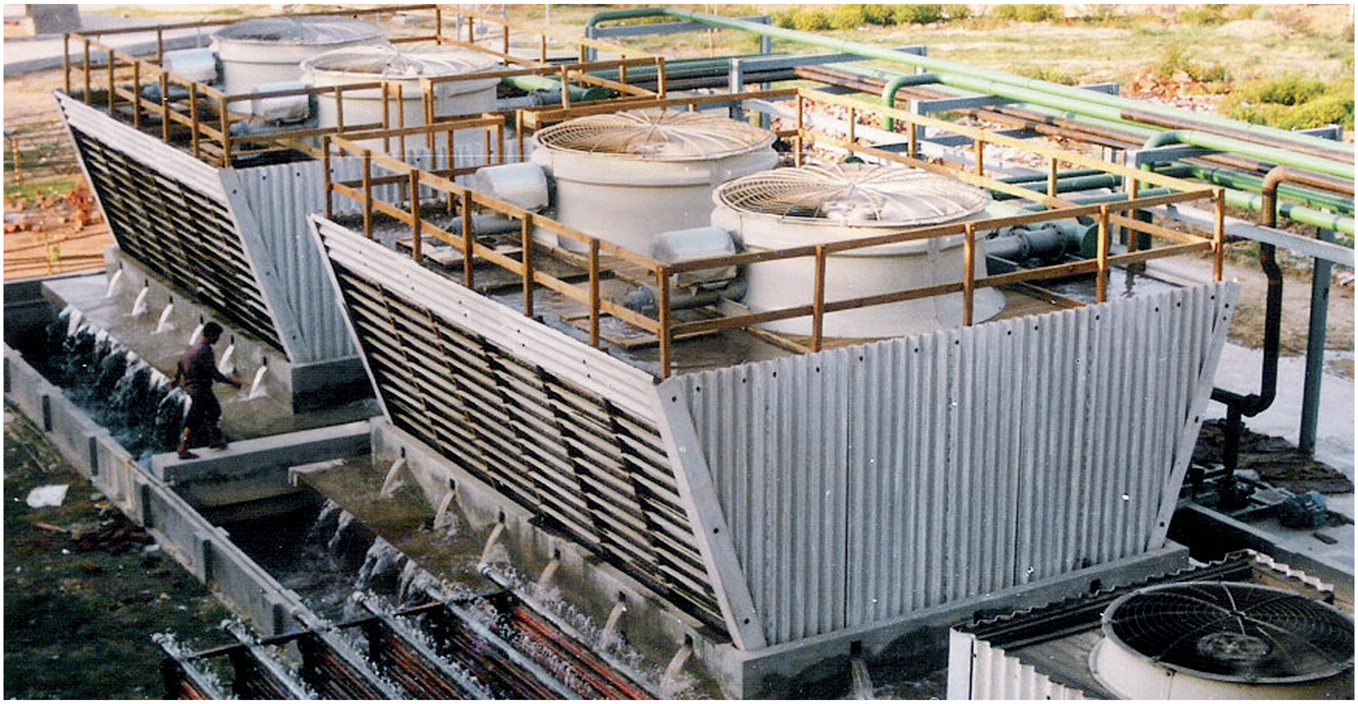
Cooling tower LWT impacts plant efficiency (photo credit Paharpur Cooling Towers Ltd.)



Predicting and Optimising
Cooling Tower Leaving Water Temperature

Raji Panicker Senior Design Lead Mechanical, CH2M, Mumbai

Introduction

Air-conditioning accounts for a large portion of the energy consumed by industrial and commercial facilities. Energy-efficient water-cooled chillers make an important contribution towards reduction of power consumption and CO_2 emissions. However, the role of the cooling tower is equally important in lowering the condenser water temperature of the chiller and, thus, lowering the power consumption. This article focuses on a counter flow cooling tower (*Figure 1*) and its prediction of cold water temperature. It is useful for checking how the tower is going to perform at varying wet bulb temperatures and air and water flows. Ideally, condenser water flow is constant or variable with air flow that can be modulated using variable frequency drive for energy saving. A method of simulation of cooling tower at various conditions has been presented. The topic of this article is only to predict cooling tower cold water temperature at different wet bulb conditions, which is important for ensuring the type of cooling tower selection and performance throughout its life cycle.

About the Author

Raji Panicker has 17 years of experience in HVAC Design, Construction and Project Management and is currently working with CH2M as Senior Design Lead Mechanical. He is a LEED AP BD+C professional from Green Business Certification Institute (GBCI), CEng (UK) and a member of USGBC and MIET.

Cooling Tower Theory

The design of a cooling tower is a competitive field of technology, and design methods and constants are proprietary information. Several types of wet cooling towers or natural draft towers exist. Wet cooling towers can be forced or induced draft, where air and water flows are cross or counter. A cooling tower makes the chiller more efficient by lowering the lift of the compressor, as shown in *Figure 2*. Chiller efficiency can be adversely affected by an improperly sized tower, inefficient fills and improper water treatment

The accepted level of performance equation of a cooling tower is:

Heat Load [Btu/hr] = 500 x Water Flow Rate [GPM] x Range [°F]

This equation does not give the thermal capability of the tower because the range is variable. It gives the heat load of the tower irrespective of the cold water temperature that we are getting. The measure of performance of the cooling tower is the resultant cold water temperature it can deliver nearest to the wet bulb condition.

Most of the projects in India now opt for CTI (Cooling Tower Institute) approved towers for guaranteed performance, or non-CTI towers as per specifications. However, whether it is a CTI or

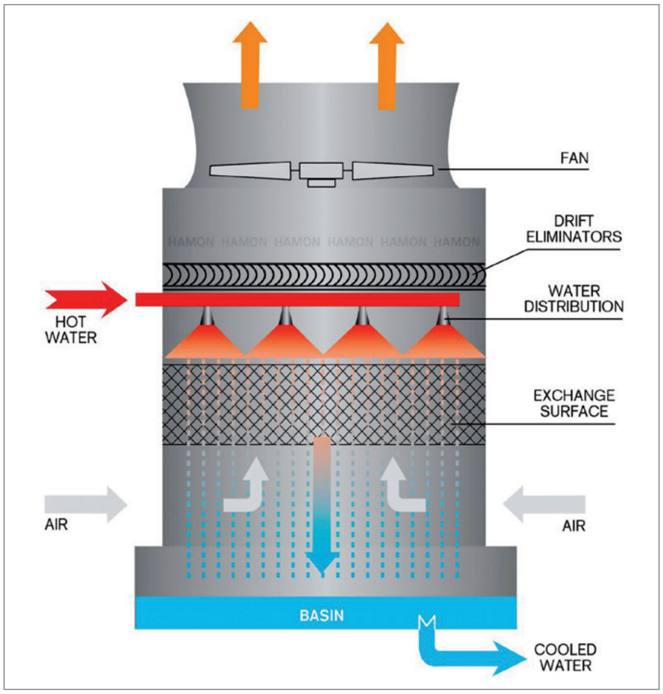


Figure 1: Counter flow Induced draft cooling tower

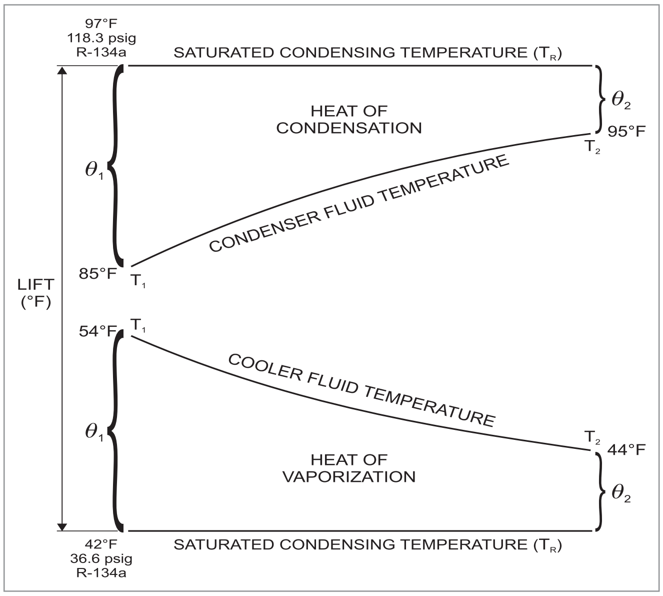


Figure 2: Compressor lift

non-CTI tower, we can always predict the cold water temperature of the cooling tower at different flow or wet bulb conditions.

The cooling tower manufacturer provides the performance curve or characteristic curve as per the design wet bulb, approach and range (*Figure 3* and *4*). In the absence of these curves, we can predict the cold water temperature based on liquid-to-gas ratio (L/G) and net transfer unit (NTU).

The theory of the cooling tower heat transfer process was developed by Merkel. Heat transfer in a cooling tower occurs by two mechanisms: transfer of sensible heat from water to air (convection), and transfer of latent heat by evaporation of water (diffusion). Both of these take place at the air-water boundary layer. The total heat transfer is the sum of this two-layer mechanism and enthalpy potential as the driving force. After manipulation of the term, Merkel equation is derived for heat transfer in a cooling tower (*Equation 1*). This is explained in a number of texts and references that may be referred by the reader, including Perry's Chemical Engineer's Handbook, ASME or ASHRAE.

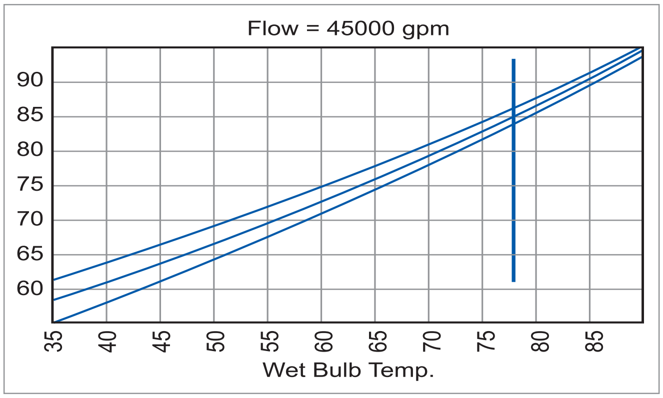


Figure 3: Cooling tower characteristics curve

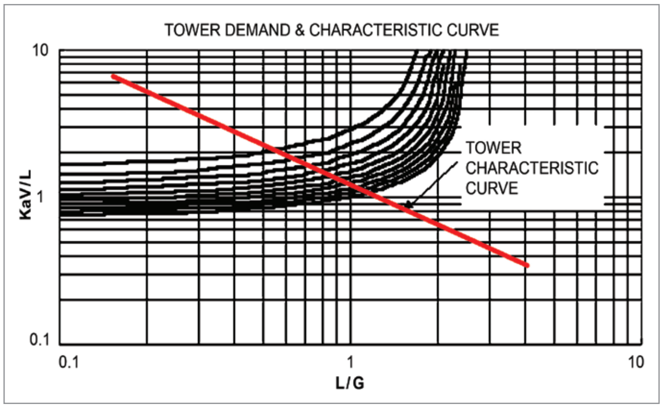


Figure 4: Cooling tower performance curve

$$\frac{KaV}{L} = \int_{T1}^{T2} \frac{Cp}{h'-ha}\,dt \qquad \text{... Equation 1}$$

Where 'K' is the overall mass transfer coefficient, 'a' is the contact area per tower volume, 'V' is the effective cooling volume per tower cross sectional area, and 'L' is the circulating water mass flow rate. The enthalpy of the air stream is 'h_a'. The enthalpy of saturated air at water temperature is 'h'. The air stream is in contact with water at different temperatures. Air does not reach the enthalpy; the driving force is the difference Δh between the enthalpies of air at air temperature and saturated air at water temperature.

$$\Delta h = h' - h_a \qquad \text{...Equation 2}$$

The tower characteristic $\frac{KaV}{L}$ or the number of net transfer units (NTU) is determined by solving the right hand side of the equation. Merkel equation is used to determine thermal demand based on the design temperature and the selected liquid-to-gas ratio (L/G).

A cooling tower can operate at wide ranges, wet bulbs, approaches and air/water flow rates. Prediction of cooling tower performance at varying conditions is important for optimal operation of chillers. Wet bulb keeps on changing as per weather conditions, which will affect the range and approach of the tower with no change in the tower characteristic $(\frac{KaV}{L})$, if flow rates of air and water are constant. Varying the fan speed through a variable frequency drive can also change the approach and tower characteristic; the same holds for water flow rate.

A cooling tower operates most of time at conditions different from the design conditions. Let us consider the example of an induced draft cooling tower at Mumbai conditions.

A cooling tower for Mumbai condition is designed at dry bulb of 95°F and wet bulb of 83°F. The difference between the inlet water temperatures 't_1' at 100°F and the outlet water temperature 't_2' at 90°F is the range. The difference between the wet bulb temperature and the outlet water temperature is the approach (a). The capacity of the cooling tower is considered as 3,125 TR, with the condenser flow rate of 7,500 gallon per min (gpm) and air flow rate of 5,07,236 cubic feet per minute (cfm).

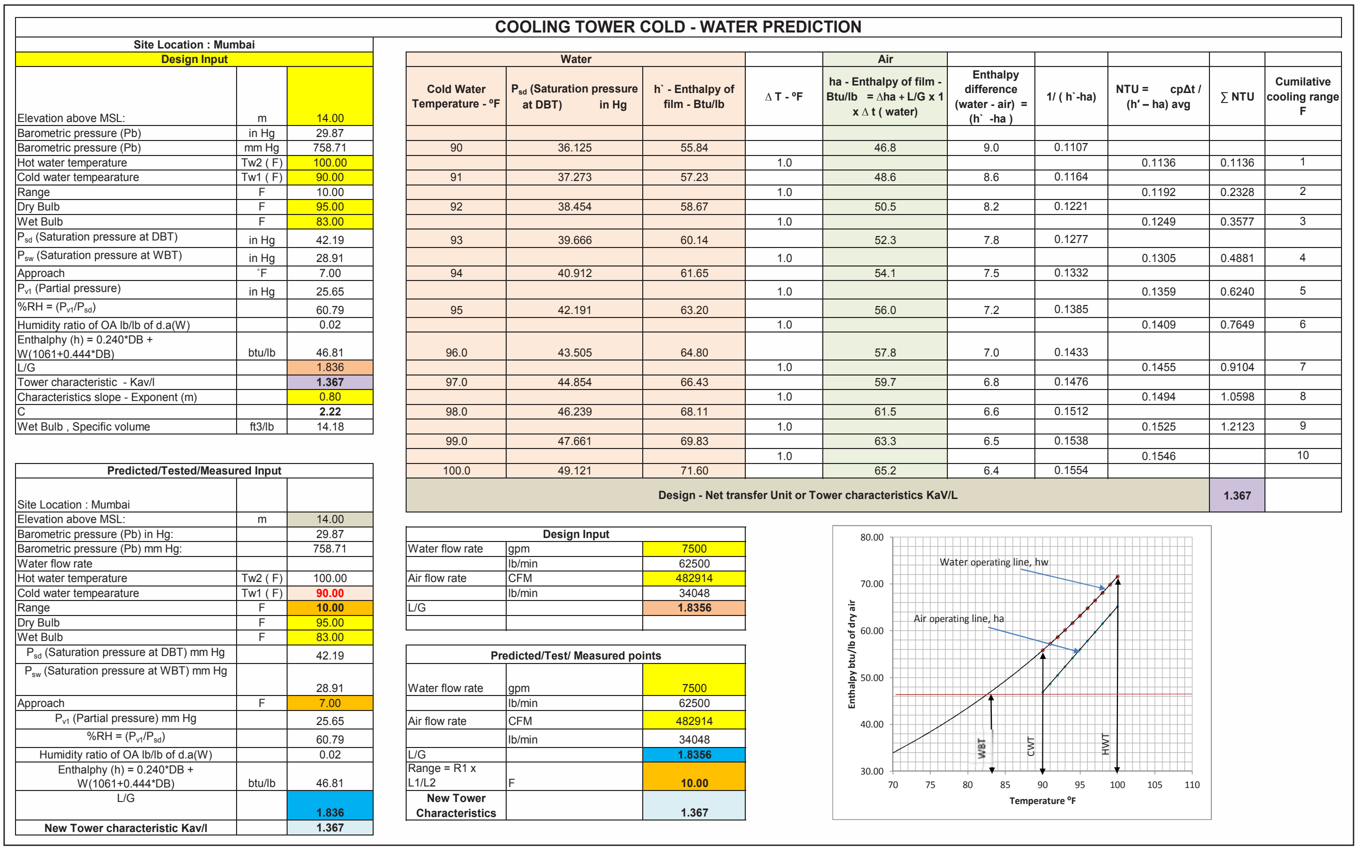
Calculating Tower Characteristics at Design Condition

The first step is to calculate L/G ('L' being the circulating water mass flow rate and 'G' being the air mass flow rate through the tower). We can use the heat balance equation, which states that heat gain by air is equal to heat loss from water.

$$\frac{L}{G} = \frac{h' - ha}{Cp(T2 - T1)} \qquad \textit{... Equation 3}$$

The procedure for L/G calculation is not explained in this article; the reader may refer the manufacturer's data sheet, *ASME PTC 23*, *CTI 105* or *ASHRAE*. The L/G ratio provided by the manufacturer for the cooling tower is 1.836.

Once we have L/G, the next step is to calculate net transfer unit (NTU). Refer *Table 1* in *Figure 5*, Column 1, which shows the water temperature followed by its corresponding saturation pressure and enthalpy. Column 4 is the range, which can be at increments of 1°F or can be divided into equal number of sections, e.g., If the range is 10°F, 5 equal section of 2°F each. Column 5 shows air temperature and its corresponding saturation pressure and enthalpy. Film enthalpies are calculated using saturation pressure and can be obtained from the psychrometric chart or calculated from my previous article on *Condensate Recovery System for Large AHU with Enthalpy Wheel*, published in the November-December 2015 issue of the *Journal*. The difference between air and water enthalpies is given in Column 6. The last-but-one column represents the incremental change in NTU for the corresponding water temperature where we get the design tower characteristics $(\frac{KaV}{L})_D$ of 1.367. *Figure 5* is also an extraction from a detailed excel calculation sheet used to predict the cold water temperature of a cooling tower at design versus new.



COOLING TOWER COLD - WATER PREDICTION

Site Location : Mumbai

Design Input

Elevation above MSL:	m	14.00
Barometric pressure (Pb)	in Hg	29.87
Barometric pressure (Pb)	mm Hg	758.71
Hot water temperature	Tw2 (F)	100.00
Cold water tempearature	Tw1 (F)	90.00
Range	F	10.00
Dry Bulb	F	95.00
Wet Bulb	F	83.00
P_{sd} (Saturation pressure at DBT)	in Hg	42.19
P_{sw} (Saturation pressure at WBT)	in Hg	28.91
Approach	˚F	7.00
P_{v1} (Partial pressure)	in Hg	25.65
%RH = (P_{v1}/P_{sd})		60.79
Humidity ratio of OA lb/lb of d.a(W)		0.02
Enthalphy (h) = 0.240*DB + W(1061+0.444*DB)	btu/lb	46.81
L/G		1.836
Tower characteristic - Kav/l		**1.367**
Characteristics slope - Exponent (m)		0.80
C		**2.22**
Wet Bulb , Specific volume	ft3/lb	14.18

Water				Air					
Cold Water Temperature - ºF	P_{sd} (Saturation pressure at DBT) in Hg	h` - Enthalpy of film - Btu/lb	Δ T - ºF	ha - Enthalpy of film - Btu/lb = Δha + L/G x 1 x Δ t (water)	Enthalpy difference (water - air) = (h` -ha)	1/ (h`-ha)	NTU = cpΔt / (h' – ha) avg	∑ NTU	Cumilative cooling range F
90	36.125	55.84		46.8	9.0	0.1107			
			1.0				0.1136	0.1136	1
91	37.273	57.23		48.6	8.6	0.1164			
			1.0				0.1192	0.2328	2
92	38.454	58.67		50.5	8.2	0.1221			
			1.0				0.1249	0.3577	3
93	39.666	60.14		52.3	7.8	0.1277			
			1.0				0.1305	0.4881	4
94	40.912	61.65		54.1	7.5	0.1332			
			1.0				0.1359	0.6240	5
95	42.191	63.20		56.0	7.2	0.1385			
			1.0				0.1409	0.7649	6
96.0	43.505	64.80		57.8	7.0	0.1433			
			1.0				0.1455	0.9104	7
97.0	44.854	66.43		59.7	6.8	0.1476			
			1.0				0.1494	1.0598	8
98.0	46.239	68.11		61.5	6.6	0.1512			
			1.0				0.1525	1.2123	9
99.0	47.661	69.83		63.3	6.5	0.1538			
			1.0				0.1546		10
100.0	49.121	71.60		65.2	6.4	0.1554			
Design - Net transfer Unit or Tower characteristics KaV/L								**1.367**	

Predicted/Tested/Measured Input

Site Location : Mumbai		
Elevation above MSL:	m	14.00
Barometric pressure (Pb) in Hg:		29.87
Barometric pressure (Pb) mm Hg:		758.71
Water flow rate		
Hot water temperature	Tw2 (F)	100.00
Cold water tempearature	Tw1 (F)	**90.00**
Range	F	**10.00**
Dry Bulb	F	95.00
Wet Bulb	F	83.00
P_{sd} (Saturation pressure at DBT) mm Hg		42.19
P_{sw} (Saturation pressure at WBT) mm Hg		28.91
Approach	F	7.00
P_{v1} (Partial pressure) mm Hg		25.65
%RH = (P_{v1}/P_{sd})		60.79
Humidity ratio of OA lb/lb of d.a(W)		0.02
Enthalphy (h) = 0.240*DB + W(1061+0.444*DB)	btu/lb	46.81
L/G		**1.836**
New Tower characteristic Kav/l		**1.367**

Design Input

Water flow rate	gpm	7500
	lb/min	62500
Air flow rate	CFM	482914
	lb/min	34048
L/G		**1.8356**

Predicted/Test/ Measured points

Water flow rate	gpm	7500
	lb/min	62500
Air flow rate	CFM	482914
	lb/min	34048
L/G		**1.8356**
Range = R1 x L1/L2	F	**10.00**
New Tower Characteristics		**1.367**

Figure 5: Design net transfer unit or tower characteristic

continued on page 46

continued from page 44

Change in Wet Bulb with Respect to Design

Once we have the tower characteristic of 1.367 as calculated above, let us vary the design wet bulb design condition.

The parameter which changes most is the ambient wet bulb. A change in wet bulb temperature does not affect the range and approach, but the tower characteristics remain unchanged. This is also shown in the calculation below.

The tower characteristic is a function of liquid-to-gas ratio, which is given by the relationship in *Equation 4*.

$$\frac{KaV}{L} = C\left(\frac{L}{G}\right)^{-Z} \qquad \text{... Equation 4}$$

Where 'z' is the slope, which is negative; if the manufacturer has not provided its value, we can use -0.6 for splash fill and -0.8 for film fill.

Assuming a different weather condition for Mumbai at dry bulb of 85°F and wet bulb of 75°F with no change in the range (10°F), L/G and tower characteristics $(\frac{KaV}{L})_D$, to determine the new tower characteristic $(\frac{KaV}{L})_N$ we have to first calculate C, which is a constant related to cooling tower design and given in *Equation 5*.

$$C=\left(\frac{KaV}{L}\right) dx \left(\frac{L}{G}\right)^{Z} \qquad \text{... Equation 5}$$

Using the calculated design parameter and substituting in *Equation 5*, we get

C=1.367 x (1.836)^0.80

C=2.22

The next step is to calculate the new tower characteristic for the assumed wet bulb condition by using *Equation 4*.

$$\frac{KaV}{L} = 2.22 \times 1.836^{-0.8}$$

$$\frac{KaV}{L} = 1.367$$

It can be seen that the change in wet bulb does not change the tower characteristic as L/G is constant. Follow the same process as shown in the table of *Figure 5* and iterate by changing the approach to match the calculated new tower characteristic. We will get cooling tower outlet water condition of 84.41°F.

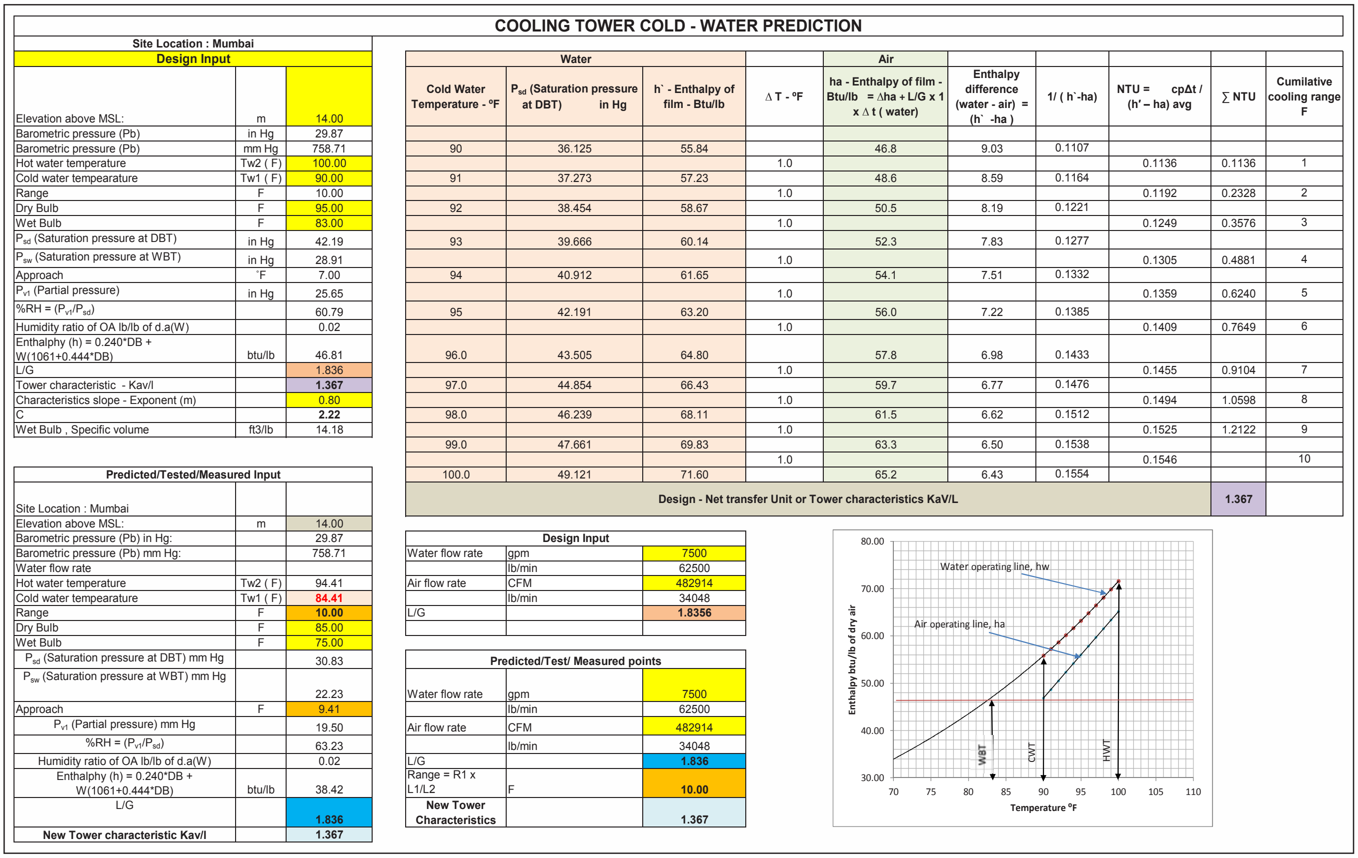
As shown in *Figure 4* for new tower characteristic, when you change the wet bulb condition, tower characteristic will change and will not match 1.367. It has to be iterated by changing the cold water temperature until you match the new tower characteristic.

Change in Liquid/Gas Ratio

In the next example, we change the liquid-to-gas ratio from 1.836 to 1.517 by assuming the above Mumbai design dry bulb/wet bulb condition.

The new calculated range will be as per *Equation 6*.

$$R2 = R1x\left(\frac{L1}{L2}\right) \qquad \text{... Equation 6}$$



COOLING TOWER COLD - WATER PREDICTION

Site Location : Mumbai		
Design Input		
Elevation above MSL:	m	14.00
Barometric pressure (Pb)	in Hg	29.87
Barometric pressure (Pb)	mm Hg	758.71
Hot water temperature	Tw2 (F)	100.00
Cold water tempearature	Tw1 (F)	90.00
Range	F	10.00
Dry Bulb	F	95.00
Wet Bulb	F	83.00
P_{sd} (Saturation pressure at DBT)	in Hg	42.19
P_{sw} (Saturation pressure at WBT)	in Hg	28.91
Approach	˚F	7.00
P_{v1} (Partial pressure)	in Hg	25.65
%RH = (P_{v1}/P_{sd})		60.79
Humidity ratio of OA lb/lb of d.a(W)		0.02
Enthalphy (h) = 0.240*DB + W(1061+0.444*DB)	btu/lb	46.81
L/G		1.836
Tower characteristic - Kav/l		**1.367**
Characteristics slope - Exponent (m)		0.80
C		**2.22**
Wet Bulb , Specific volume	ft3/lb	14.18

Predicted/Tested/Measured Input		
Site Location : Mumbai		
Elevation above MSL:	m	14.00
Barometric pressure (Pb) in Hg:		29.87
Barometric pressure (Pb) mm Hg:		758.71
Water flow rate		
Hot water temperature	Tw2 (F)	94.41
Cold water tempearature	Tw1 (F)	**84.41**
Range	F	**10.00**
Dry Bulb	F	85.00
Wet Bulb	F	75.00
P_{sd} (Saturation pressure at DBT) mm Hg		30.83
P_{sw} (Saturation pressure at WBT) mm Hg		22.23
Approach	F	9.41
P_{v1} (Partial pressure) mm Hg		19.50
%RH = (P_{v1}/P_{sd})		63.23
Humidity ratio of OA lb/lb of d.a(W)		0.02
Enthalphy (h) = 0.240*DB + W(1061+0.444*DB)	btu/lb	38.42
L/G		**1.836**
New Tower characteristic Kav/l		**1.367**

Water				Air					
Cold Water Temperature - ºF	P_{sd} (Saturation pressure at DBT) in Hg	h` - Enthalpy of film - Btu/lb	Δ T - ºF	ha - Enthalpy of film - Btu/lb = Δha + L/G x 1 x Δ t (water)	Enthalpy difference (water - air) = (h` -ha)	1/ (h`-ha)	NTU = cpΔt / (h' – ha) avg	∑ NTU	Cumilative cooling range F
90	36.125	55.84		46.8	9.03	0.1107			
			1.0				0.1136	0.1136	1
91	37.273	57.23		48.6	8.59	0.1164			
			1.0				0.1192	0.2328	2
92	38.454	58.67		50.5	8.19	0.1221			
			1.0				0.1249	0.3576	3
93	39.666	60.14		52.3	7.83	0.1277			
			1.0				0.1305	0.4881	4
94	40.912	61.65		54.1	7.51	0.1332			
			1.0				0.1359	0.6240	5
95	42.191	63.20		56.0	7.22	0.1385			
			1.0				0.1409	0.7649	6
96.0	43.505	64.80		57.8	6.98	0.1433			
			1.0				0.1455	0.9104	7
97.0	44.854	66.43		59.7	6.77	0.1476			
			1.0				0.1494	1.0598	8
98.0	46.239	68.11		61.5	6.62	0.1512			
			1.0				0.1525	1.2122	9
99.0	47.661	69.83		63.3	6.50	0.1538			
			1.0				0.1546		10
100.0	49.121	71.60		65.2	6.43	0.1554			
Design - Net transfer Unit or Tower characteristics KaV/L								**1.367**	

Design Input		
Water flow rate	gpm	7500
	lb/min	62500
Air flow rate	CFM	482914
	lb/min	34048
L/G		**1.8356**

Predicted/Test/ Measured points		
Water flow rate	gpm	7500
	lb/min	62500
Air flow rate	CFM	482914
	lb/min	34048
L/G		**1.836**
Range = R1 x L1/L2	F	**10.00**
New Tower Characteristics		**1.367**

Figure 6: New tower characteristic and prediction of cold water temperature

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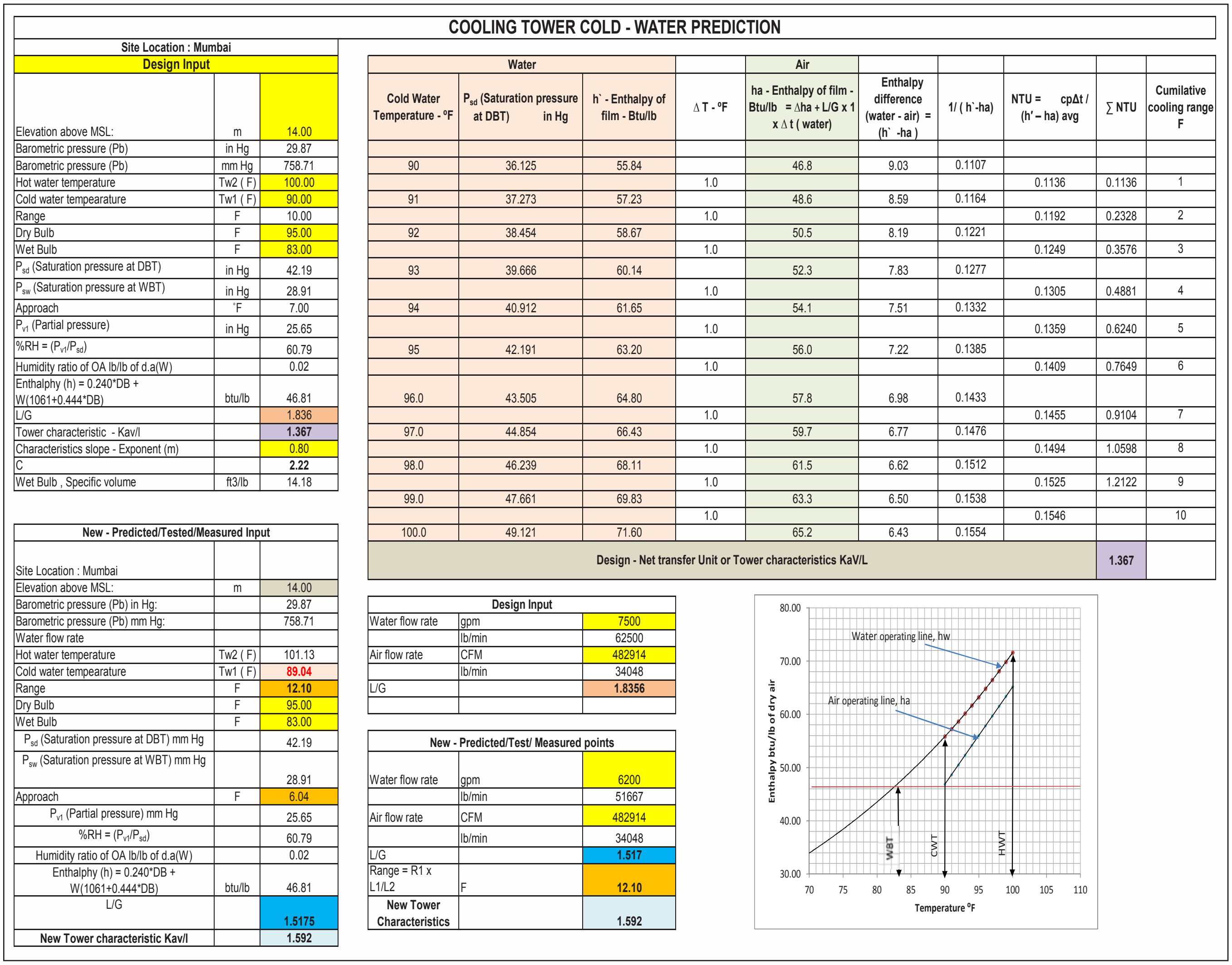

COOLING TOWER COLD - WATER PREDICTION

Site Location : Mumbai		
Design Input		
Elevation above MSL:	m	14.00
Barometric pressure (Pb)	in Hg	29.87
Barometric pressure (Pb)	mm Hg	758.71
Hot water temperature	Tw2 (F)	100.00
Cold water tempearature	Tw1 (F)	90.00
Range	F	10.00
Dry Bulb	F	95.00
Wet Bulb	F	83.00
P_{sd} (Saturation pressure at DBT)	in Hg	42.19
P_{sw} (Saturation pressure at WBT)	in Hg	28.91
Approach	˚F	7.00
P_{v1} (Partial pressure)	in Hg	25.65
%RH = (P_{v1}/P_{sd})		60.79
Humidity ratio of OA lb/lb of d.a(W)		0.02
Enthalphy (h) = 0.240*DB + W(1061+0.444*DB)	btu/lb	46.81
L/G		1.836
Tower characteristic - Kav/l		**1.367**
Characteristics slope - Exponent (m)		0.80
C		**2.22**
Wet Bulb , Specific volume	ft3/lb	14.18

Water				Air					
Cold Water Temperature - ºF	P_{sd} (Saturation pressure at DBT) in Hg	h` - Enthalpy of film - Btu/lb	∆ T - ºF	ha - Enthalpy of film - Btu/lb = ∆ha + L/G x 1 x ∆ t (water)	Enthalpy difference (water - air) = (h` -ha)	1/ (h`-ha)	NTU = cp∆t / (h' – ha) avg	∑ NTU	Cumilative cooling range F
90	36.125	55.84		46.8	9.03	0.1107			
			1.0				0.1136	0.1136	1
91	37.273	57.23		48.6	8.59	0.1164			
			1.0				0.1192	0.2328	2
92	38.454	58.67		50.5	8.19	0.1221			
			1.0				0.1249	0.3576	3
93	39.666	60.14		52.3	7.83	0.1277			
			1.0				0.1305	0.4881	4
94	40.912	61.65		54.1	7.51	0.1332			
			1.0				0.1359	0.6240	5
95	42.191	63.20		56.0	7.22	0.1385			
			1.0				0.1409	0.7649	6
96.0	43.505	64.80		57.8	6.98	0.1433			
			1.0				0.1455	0.9104	7
97.0	44.854	66.43		59.7	6.77	0.1476			
			1.0				0.1494	1.0598	8
98.0	46.239	68.11		61.5	6.62	0.1512			
			1.0				0.1525	1.2122	9
99.0	47.661	69.83		63.3	6.50	0.1538			
			1.0				0.1546		10
100.0	49.121	71.60		65.2	6.43	0.1554			
Design - Net transfer Unit or Tower characteristics KaV/L								**1.367**	

New - Predicted/Tested/Measured Input		
Site Location : Mumbai		
Elevation above MSL:	m	14.00
Barometric pressure (Pb) in Hg:		29.87
Barometric pressure (Pb) mm Hg:		758.71
Water flow rate		
Hot water temperature	Tw2 (F)	101.13
Cold water tempearature	Tw1 (F)	**89.04**
Range	F	**12.10**
Dry Bulb	F	95.00
Wet Bulb	F	83.00
P_{sd} (Saturation pressure at DBT) mm Hg		42.19
P_{sw} (Saturation pressure at WBT) mm Hg		28.91
Approach	F	6.04
P_{v1} (Partial pressure) mm Hg		25.65
%RH = (P_{v1}/P_{sd})		60.79
Humidity ratio of OA lb/lb of d.a(W)		0.02
Enthalphy (h) = 0.240*DB + W(1061+0.444*DB)	btu/lb	46.81
L/G		**1.5175**
New Tower characteristic Kav/l		**1.592**

Design Input		
Water flow rate	gpm	7500
	lb/min	62500
Air flow rate	CFM	482914
	lb/min	34048
L/G		**1.8356**

New - Predicted/Test/ Measured points		
Water flow rate	gpm	6200
	lb/min	51667
Air flow rate	CFM	482914
	lb/min	34048
L/G		**1.517**
Range = R1 x L1/L2	F	**12.10**
New Tower Characteristics		**1.592**

Figure 7: Cold water prediction with new tower characteristic and L/G ratio.

'R1' is the range, which is 10˚F; 'L1' is 7500 gpm; and 'L2' is the new flow rate, which is 6200 gpm.

Using this value, we derive the new range 'R2' which is 12.10˚F. Next we calculate 'C' by following *Equation 1*.

$$\frac{KaV}{L} = 2.2 \text{ x } 1.517^{-0.8}$$

$$\frac{KaV}{L} = 1.592$$

The new tower characteristic is 1.592 (refer *Figure 7*). Follow the same process by iterating the approach to match the new characteristic, and the cold water temperature comes to about 89.04°F.

Conclusion

This article demonstrates rather pointedly that cooling tower performance and operation are not so straightforward as they are often thought to be. It is quite evident that the maximum efficiency is delivered by water cooled chillers, which are used in major projects worldwide. Even 1˚F drop in condensor water temperature can save upto 2% energy of chiller which can, in turn, reduce global carbon emission. An undersized or non-peforming cooling tower may not deliver the right cold water temperature due to which the chiller would consume more power than required.

It is necessary to have a working knowledge of the performance of cooling towers, without misconception, in order to purchase and operate them to the best advantage for maximum production at minimum cost.

References

1. The American Society of Mechanical Engineers, *Atmoshpheric Cooling Tower Equipment*, ASME PTC 23 - 1986
2. Cooling Technology Institute, CTI 105, *Acceptance Test of Water Cooling Tower*
3. ASHRAE, *HVAC System and Equipment 2012*, Cooling Tower (Chapter 40)
4. Perry's Chemical Engineer's Handbook, 7th Edition, *Psychrometry, Evaporative Cooling and Solids Drying*

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