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An Improved Cooling Tower Algorithm for the CoolTools^{TM} Simulation Model

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ABSTRACT

An improved cooling tower simulation algorithm was developed for the CoolTools™ simulation model to support the optimal design of chilled water systems. The new algorithm was developed to predict more quickly and more accurately the thermal performance and energy consumption of a cooling tower. An array of previously known analytical and empirical algorithms and the newly developed empirical algorithm were evaluated on the basis of accuracy and computational efficiency. The accuracy of each algorithm was determined for a given set of operating conditions by a comparison between the computed approach to the inlet wet-bulb temperature (approach) and that determined from vendor-supplied performance curves. The results of the evaluation indicate that the empirical algorithms require considerably less computational time and provide more consistent results than do the analytical algorithms. The new empirical algorithm was found to be more accurate and more efficient than the previously existing algorithms.

INTRODUCTION

The CoolTools™ simulation model employing the DOE2 simulation code is used for building energy analyses and optimizations. An important component of this model is the chilled water system that utilizes "package" type evaporative cooling towers. The expected performance of these evaporative cooling towers is based on cooling tower simulation algorithms (CTSAs). A literature review was conducted to identify the existing CTSAs. An improved CTSA was developed and compared with the existing CTSAs for speed and accuracy to determine the best CTSA to be used by the DOE2 simulation code. The accuracy of each CTSA was determined for a given set of operating conditions by a comparison between the computed approach and that determined from vendor-supplied performance curves for an array of cooling towers that have been certified by the Cooling Tower Institute.

In 1925, Dr. Fredrick Merkel (1925) proposed a theory relating evaporation and sensible heat transfer where there is counterflow contact of water and air, such as in cooling towers. Merkel made several simplifying assumptions that reduce the governing relationships for a counterflow cooling tower to a single separable ordinary differential equation. Several authors have presented the derivation of the Merkel equation (Lefevre 1984; Feltzin and Benton 1991; Bowman and Benton 1996). This equation expresses the number of transfer units (NTU) as a function of the integral of the temperature difference divided by the enthalpy gradient in a cooling tower. Since the boundary conditions are known, the integral may be integrated. Merkel used the four-point Tchebycheff method. Merkel posited that the bulk water in contact with a stream of air is surrounded by a film of saturated air and that the saturated air is surrounded by a bulk stream of air. He made the following assumptions:

1. The saturated air film is at the temperature of the bulk water.
2. The saturated air film offers no resistance to heat transfer.
3. The vapor content of the air is proportional to the partial pressure of the water vapor.
4. The heat transferred from the air to the film by convection is proportional to the heat transferred from the film to the ambient air by evaporation.

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5. The specific heat of the air-water vapor mixture and the heat of vaporization are constant.
6. The loss of water by evaporation is neglected.
7. The force driving heat transfer is the differential enthalpy between the saturated and bulk air.

In 1943, a corporation plotted NTU as a function of the cooling tower liquid to gas (*L/G*) ratio to plot cooling tower demand curves. Numerous approaches have been devised in an attempt to compensate for several of the above assumptions. Mickley (1949) introduced temperature and humidity gradients with heat and mass transfer coefficients from the water to the film of saturated air and from the film to the bulk stream of air. Baker and Mart (1952) developed the concept of a "hot water correction factor." Snyder (1955) developed an empirical equation for an overall enthalpy transfer coefficient per unit of volume of fill material in a crossflow cooling tower based on tests that he conducted. Zivi and Brand (1956) extended the analysis of Merkel to crossflow cooling towers. Lowe and Christie (1961) performed laboratory studies on several types of counterflow fill. Hallett (1975) presented the concept of a cooling tower characteristic curve where the NTU is expressed as an empirically derived function of the *L/G* ratio. Kelly (1976) used the model of Zivi and Brand along with laboratory data to produce a volume of crossflow cooling tower characteristic curves and demand curves.

Penney and Spalding (1979) introduced a model for natural draft cooling towers using a finite difference method. Majumdar and Singhal (1981) extended the model to mechanical draft cooling towers. Johnson et al. (1983) proposed a computer model based on the NTU-effectiveness approach used for heat exchangers. Bourillot (1983a, 1983b) developed the TEFERI computer model based on heat and mass transfer equations similar to Zivi and Brand. The TEFERI model assumes uniform water and air temperatures and flow rates at the inlet and calculates the loss of water due to evaporation, so the water flow rate does not remain uniform as it passes through the cooling tower.

Benton (1983) developed the FACTS model, which employs an integral formulation of the equations for conservation of the mass of air and water vapor, conservation of energy, and the Bernoulli equation to arrive at a numerical solution apart from the Merkel analogy. FACTS can accommodate variable inlet water and air temperatures and hybrid fills, but it assumes a constant water flow rate through the tower (Benton 1984). Benton and Waldrop (1988) and Bowman and Benton (1995) presented the results of comparisons between FACTS and test data. FACTS is widely used by utilities to model cooling tower performance. Majumdar et al. (1983) developed the VERA2D model. VERA2D treats air flow in the cooling tower as two-dimensional and steady and water flow as one-dimensional.

Lefevre (1984) revisited the energy balance between water and air that was the original basis for the Merkel equation. The heat loss from the water (i.e., the water flow rate times the specific heat of water times the change in the water temperature plus the heat lost by evaporation) is equal to the heat gained by the air (i.e., the air flow rate times the change in the air enthalpy). Both terms are equal to the mass transfer coefficient times the enthalpy difference times the interface area per unit of volume times the incremental cooling volume. Whereas Merkel used a simplified expression for the heat loss from the water to arrive at his equation, Lefevre used the expression for the heat gain of the air. Lefevre arrived at an expression for the NTU as a function of the gas to liquid ratio (that he assumed to be constant) and the air enthalpies. Lefevre applied a dimensionless correction factor to compensate for the model's shortcomings at higher water temperatures.

Vance (1984) presented methods for adjusting the performance of a mechanical draft cooling tower for off-design air and water mass flow rates. Fulkerson (1988) reported heat transfer and pressure drop data for counterflow cooling towers at vendor test facilities. The ability of several computer codes to predict the results of tests conducted by the Electric Power Research Institute (EPRI) on eight crossflow and eight counterflow fills was reported by Bell et al. (1989). Benton (1989) showed that both the Gauss and Lobatto methods of numerical integration are superior to the four-point Tchebycheff method for determining the number of transfer units. Feltzin and Benton (1991) derived a more exact model and compared the results of this model to the Merkel equation. The Feltzin and Benton model did not include an empirical temperature correction factor. Desjardins (1992) analyzed the EPRI test data by employing the concept of an "offset" hot water temperature as proposed by Mickley (1949) and the more exact method of Feltzin and Benton. Twelve CTSAs were identified from this research for further consideration.

DEVELOPMENT OF THE IMPROVED CTSA

The objective of the improved CTSA was to accurately reproduce cooling tower performance and energy consumption given minimal tower specifications. The first phase of development was based on vendor-supplied cooling tower performance data. A second phase will be based on field measurements taken on operating towers. The minimal required tower specifications are a single design or operating point whether the cooling tower is of the crossflow or counterflow design. Several operating points can be used to compute an equivalent single design point. Model selection for inclusion in DOE2 simulation code was based on the following criteria:

1. Computational speed (as many calculations are required for simulation and optimization)
2. Simplicity of data input (i.e., only data that are commonly available to the intended user)
3. Ability to simulate response (i.e., variation of all major operating parameters)
4. Accuracy
5. Algorithm availability (i.e., free of legal encumbrance)

6. Compatible source code (viz., FORTRAN)
7. Completeness (i.e., not dependent on excessive auxiliary functions or extensive libraries)
8. Compactness (i.e., small enough to be included as an internal function of a larger code)
9. Computational stability (i.e., not producing sporadic run-time errors, such as division by zero or square-root of a negative number)
10. Robustness (i.e., consistently convergent with meaningful output for meaningful input)
11. Range of applicability (viz., must cover the normal range of operation for package type towers)

Three of the CTSAs identified in the background research, the TEFERI, FACTS, and VERA2D models, were discarded because they failed to meet criteria 1, 2, 6, 8, and/or 10 above. The following CTSAs were encoded and tested: DOE2 version 2.1D, DOE2 version 2.1E, DOE2 version 2.2, the Merkel method, LeFevre method, Benton and Feltzin implementation of the LeFevre version, the "more nearly exact" (exact) method, the LMTD method, and the NTU-effectiveness method. Of these CTSAs, which represent a mixture of empirical and simple analytical algorithms, the following were selected for further investigation:

1. The DOE2 version 2.2, a 12-parameter multi-variable curve fit.
2. The Merkel method with the four-point Tchebycheff integration method.
3. The Benton and Feltzin implementation of the LeFevre method using the Lobatto quadrature instead of the Romberg numerical integration method.
4. The Benton and Feltzin exact method, a set of simultaneous nonlinear ordinary differential equations using the Runge-Kutta method of integration.
5. The NTU-effectiveness method, a modified version of the CTSA developed by the Environmental Protection Agency (EPA).

The accuracy of each CTSA was measured by computing approach temperature as a function of wet-bulb temperature, cooling range, water flow rate, and fan power, based on a single design point and by comparing this temperature to vendor-supplied data. None of the identified existing CTSAs compute approach directly from these other parameters; rather, the approach is required as input. As the accuracy was measured by the computed approach, the most logical way to achieve the greatest accuracy was to develop a CTSA that provides approach directly. For a fixed complexity, this would also be the most efficient way to compute tower performance when it is expressed as an approach temperature. Preliminary testing of the existing models described above indicated that an empirical algorithm would best meet the current objectives. Therefore, the improved algorithm is a regression model based on the approach. Separate correlation coefficients were developed based on crossflow and counterflow data sets.

The task of generating this empirical expression for the improved CTSA is basically one of multi-variable regression. Here, the dependent variable is approach and the independent variables are wet bulb, range, water flow, and fan power. Many developers have tackled this problem for empirically computing cooling tower performance. The previous efforts identified have grouped the independent variables and developed sequential regression models for the dependent variable or some intermediate parameter used to compute the dependent variable. All previous versions of the DOE2 CTSAs use some form of sequential regression on grouped parameters. This approach treats each additional independent variable or group of independent variables as a correction. Grouping the independent variables presumes significant interrelationships within the groups. Separating the parameters presumes negligible interrelationships among the groups. Overlapping the groups (i.e., one or more independent variables appearing in more than one group) increases the regression error, as each sequential regression must also minimize the systematic residuals left over from the previous regression. This regression problem is evidenced by an increasing number of coefficients without significant reduction in error.

Simultaneous regression on all the independent variables is the best approach to minimize the error over an entire data set. Linear least-squares regression was used. A power expansion involving all the independent variables is the simplest form, allowing interaction among all of the variables. A zero-order expansion yields a single term and coefficient. A first-order expansion of four independent variables yields five terms and coefficients. A second-order expansion, including every possible combination up to a power of two, yields 15 terms. A third-order expansion yields 35 terms and so on. A third-order expansion proved to be the most satisfactory for the present development, yielding the highest regression coefficient. The new CTSA is basically a higher-order, multi-parameter enhancement of the DOE2 rating functions based on approach rather than rating.

Two problems arose in practical applications of such a regression involving so many terms. The first problem was a result of finite digital accuracy. The least-squares matrix becomes increasingly graded as the number of terms increases. A graded matrix is one having very large and very small terms that are all significant. With finite-precision calculations, the small terms are lost, and the resulting agreement is poor. In order to minimize this problem, 80-bit precision was used throughout, along with maximal preconditioning of the regression matrix. Intel 80-bit floating-point numbers have a range of $10^{\pm 4092}$ and provide approximately 18 significant figures. The second problem that arose was that of erratic behavior. A high-order regression may fit the data points quite well yet produce unreasonable results between and outside the data points (i.e., interpolation and extrapolation). Data point weighting was used to control erratic behavior. Erratic behavior is most pronounced at extreme values of the independent variables (e.g., at very high range or very low wet bulb). Multi-dimensional graphics, such as Figures 1 and 2 showing isosurfaces and slicing planes, were used to identify erratic behavior. Where erratic behavior was identified, neighboring data points were weighted more heavily until the desired asymptotic behavior was obtained. The desired asymptotic behavior is shown in Figure 1 by the contours drawn in the slicing planes and in Figure 2 by the curvature of the sheets of constant rating. This process necessarily increases the residual at other data points, but it greatly improves extrapolation, which is a key objective of the improved CTSA.

The crossflow vendor-supplied data contained little variation of the water flow and few points for low wet bulbs. The FACTS computer code was used to extend these vendor data and provide control points. This was accomplished by numerically modeling a tower of approximately the correct size, adjusting its characteristics until it best fit the vendor data, and then performing calculations at very low and high water flow and low wet bulb. These additional control points are shown as diamonds in Figure 3, whereas the vendor data are shown as spheres.

All of the existing CTSAs require some correction for fan power. Five fan power corrections were identified. These include the curves from DOE2 versions 2.1E and 2.2, a nomograph published by Wood and Betts (1950), a curve obtained from Hudson fan performance curves using the FACTS model, and the one-third power law (i.e., air flow is proportional to the cube-root of the fan power). The improved CTSA does not require such a correction, as this variation was incorporated in the multi-variable regression. The regression was performed based on normalized fan power and normalized fan speed. The coefficients differ, but the results are essentially the same. Either form could be used for computational convenience.

EXPERIMENTAL DESIGN

Three tower models from each of four vendors, or a total of 12 models, were used for testing the CTSAs. Three of the models from one vendor had three variations, making a total of 16 data sets shown in Table 1. All towers were "package" type with heat capacities ranging from 46 to 1667 tons. Towers 1, 2, and 3 are manufactured by vendor A. Towers 1 and 2 had the same design point but are crossflow and counterflow, respectively. These selections speak to the ability of the CTSAs to account for different flow orientations. Tower 3 was selected because it is the largest model in the same type group as tower 2. Towers 4, 5, and 6 are manufactured by vendor B. Towers 4 and 2 have the same design point and configuration, thus providing a direct comparison between these two vendors. Towers 5 and 6 are a large-range/close-approach and smaller-range/larger-approach tower, respectively, providing another test of the CTSAs. Towers 7, 8, and 9 are manufactured by vendor C. Tower 8 is the closest available model to

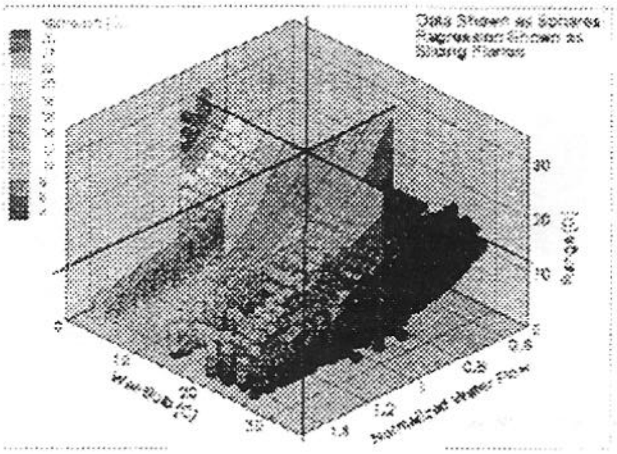

Figure 1 *Counterflow approach data and regression.*

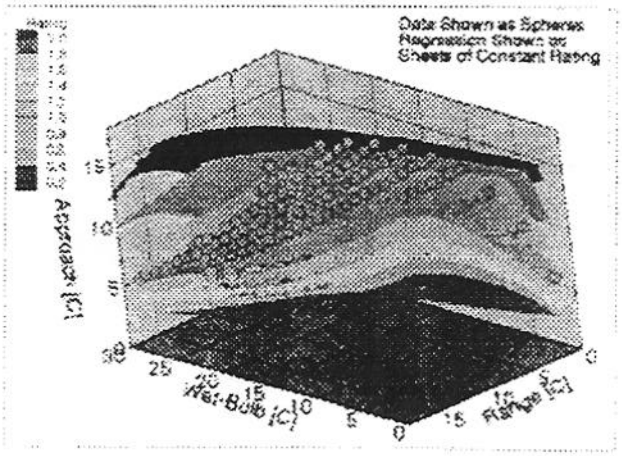

Figure 2 *Counterflow rating data and regression.*

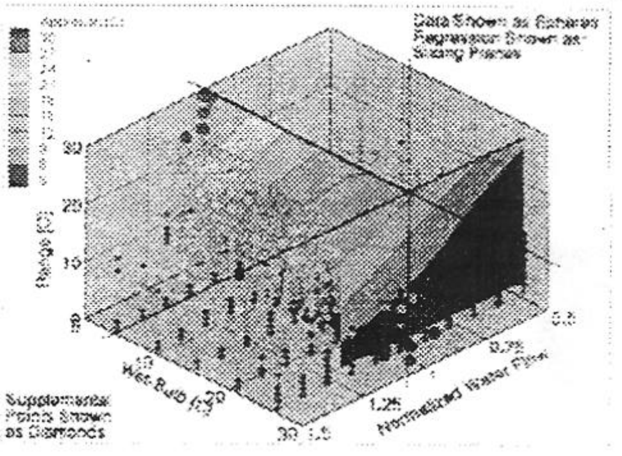

Figure 3 *Crossflow data, regression, and control points.*

the baseline design point and another crossflow reference point. Towers 7 and 9 provide additional variation of parameters. Towers 10, 11, and 12 are manufactured by vendor D. These models come with three fan motor sizes each (i.e., A, B, and C). The single cell "box" size is the same for all models. Towers 10, 11, and 12 are identical except for the fill, thus providing a different test of CTSAs.

TABLE 1
Vendor Towers

Tower	Vendor	Type	Water Flow (m^3/s)	Fan Power (kW)	Wet Bulb (°C)	Range (°C)	Approach (°C)	Heat Load (kW)
1	A	XF	0.06309	11.2	25.6	5.6	3.9	1170
2	A	CF	0.06309	29.8	25.6	5.6	3.9	1170
3	A	CF	0.15773	89.5	12.8	11.1	11.1	5859
4	B	CF	0.06309	14.9	25.6	5.6	3.9	1170
5	B	CF	0.02208	11.2	15.6	11.1	5.6	819
6	B	CF	0.31545	74.6	15.6	5.6	8.3	5859
7	C	XF	0.03842	7.5	25.6	5.6	3.9	713
8	C	XF	0.05886	11.2	25.6	5.6	3.9	1093
9	C	XF	0.10372	29.8	25.6	5.6	3.9	1926
10A	D	CF	0.01457	2.2	25.6	5.6	3.9	271
10B	D	CF	0.01685	3.7	25.6	5.6	3.9	313
10C	D	CF	0.01893	5.6	25.6	5.6	3.9	351
11A	D	CF	0.01022	2.2	25.6	5.6	3.9	190
11B	D	CF	0.01192	3.7	25.6	5.6	3.9	221
11C	D	CF	0.01344	5.6	25.6	5.6	3.9	250
12A	D	CF	0.00871	2.2	25.6	5.6	3.9	162
12B	D	CF	0.01022	3.7	25.6	5.6	3.9	190
12C	D	CF	0.01173	5.6	25.6	5.6	3.9	218

RESULTS

The five existing algorithms and the new algorithm all satisfy the basic selection criteria; however, they do vary in computational speed and accuracy. The CTSAs can be separated into two categories: analytically based and empirically based. Typically, the analytically based CTSAs are significantly slower than those that are empirically based. The analytically based CTSAs can further be separated into two categories: those requiring numerical integration of one or more differential equations (viz., Feltzin and Exact) and those requiring evaluation of a simple equation (Merkel and NTU-effectiveness). The computational speed of each of the CTSAs compared to the base case is listed in Table 2.

The only required user input data is the design point, which includes the fan power, water flow rate, wet bulb, range, and approach and whether the tower is crossflow or counterflow. Although the CTSAs have not yet been tested against field data, the input requirements are the same. It is expected that the CTSAs would be used to compute an average implied test point (analogous to the design point) when analyzing field data from a single tower. The accuracy of each of the candidate CTSAs has been tested against the vendor data. This comparison includes 669 data points for the counterflow towers and

TABLE 2
Comparison of Speed*

DOE2 Version 2.2	1.00
Merkel	5.49
NTU-Effectiveness	3.17
Feltzin	101.7
Exact	100.9
New Counterflow	0.0013
New Crossflow	0.0015

* Note: As the new CTSA provides approach directly, there are considerable computational savings, even though the function itself involves 35 constants and approximately six times as many operations. The new CTSA provides no computational benefit when iteratively computing available water flow capacity or required fan power.

347 data points for the crossflow towers. The results are summarized in Tables 3 and 4.

Figure 4 shows a comparison between the error computed by the DOE2 version 2.2 CTSA and the new CTSA for Tower 1, a crossflow tower, operating at the rated flow of 1000 gpm.

TABLE 3
CTSA Accuracy for Counterflow Cooling Towers (°C)

CTSA	DOE2 V2.2	Merkel	NTU-Effectiveness	Feltzin	Exact	Cnew
Average Error	0.0	0.1	0.2	0.1	0.1	0.0
Maximum Error	1.7	1.6	3.9	1.4	1.4	0.9
Standard Deviation	0.4	0.4	1.0	0.4	0.4	0.3
95% Confidence Interval*	0.8	0.9	2.0	0.8	0.8	0.5

* Note: The 95% confidence interval is a revealing statistical measure of the CTSA's accuracy because it takes into account the deviation and the sample size. The 95% confidence interval for the new CTSA is approximately two-thirds that of DOE2 version 2.2.

TABLE 4
CTSA Accuracy for Crossflow Cooling Towers (°C)

CTSA	DOE2 V2.2	Merkel	NTU-Effectiveness	Feltzin	Exact	Cnew
Average Error	–0.2	0.2	–0.4	0.2	0.2	0.1
Maximum Error	2.2	1.4	2.3	1.4	1.4	1.2
Standard Deviation	0.4	0.3	0.6	0.3	0.3	0.3
95% Confidence Interval*	0.8	0.6	1.2	0.6	0.6	0.6

* Note: The 95% confidence interval is a revealing statistical measure of the CTSA's accuracy because it takes into account the deviation and the sample size. The 95% confidence interval for the new CTSA is approximately two-thirds that of DOE2 version 2.2.

TABLE 5
CTSA Accuracy for Crossflow and Counterflow Cooling Towers (°C)

CTSA	DOE2 V2.2	Merkel	NTU-Effectiveness	Feltzin	Exact	Cnew
Tower 1 (XF) Std. Dev.	0.20	0.16	0.49	0.13	0.13	0.11
Tower 2 (CF) Std. Dev.	0.29	0.39	0.54	0.36	0.36	0.26

The error is the difference between the cold water temperature predicted by the CTSA and that predicted by the cooling tower vendor. For this cooling tower, the new CTSA is well behaved in comparison with DOE2 version 2.2. The 95% confidence interval is approximately half that of DOE2 version 2.2 (0.19 vs. 0.36).

A comparison may be made between towers 1 and 2, which have the same design point but are crossflow and counterflow, respectively. This comparison, shown in Table 5, indicates that all of the CTSAs, including the new CTSA, more accurately predict the performance of the crossflow tower than the counterflow tower. These results include 96 data points. Figures 4 and 5 show the computed error as a function of the wet-bulb temperature for an array of cooling ranges for DOE2 version 2.2 and the new CTSAs. These results show that for the counterflow tower, the error computed by the new CTSA increases with increasing range as do the other CTSAs (see Figure 5). For the case of tower 2, the new CTSA is not as well behaved as the DOE2 version 2.2 CTSA at higher ranges.

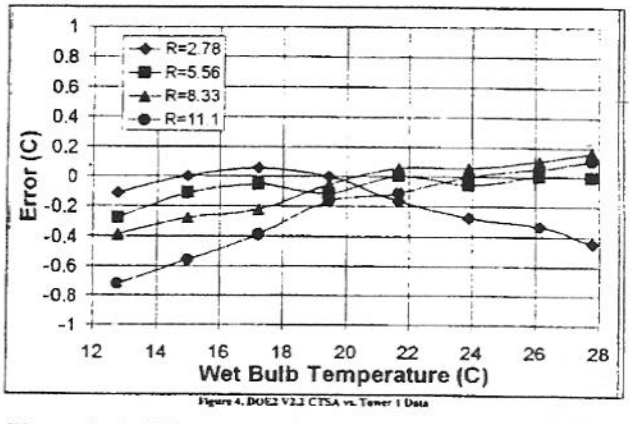

Figure 4 *DOE2 version 2.2 CTSA vs. tower 1 data.*

Table 6 and Figures 5 and 6 show a comparison between towers 2 and 4. These counterflow towers have the same

TABLE 6
CTSA Accuracy for Vendors A and B (°C)

CTSA	DOE2 V2.2	Merkel	NTU-Effectiveness	Feltzin	Exact	Cnew
Tower 2 Std. Dev. (96 pts.)	0.29	0.39	0.54	0.36	0.36	0.26
Tower 4 Std. Dev. (85 pts.)	0.27	0.14	0.46	0.15	0.15	0.16

TABLE 7
Accuracy for Large-Range/Close-Approach and Smaller-Range/Larger Approach (°C)

CTSA	DOE2 V2.2	Merkel	NTU-Effectiveness	Feltzin	Exact	Cnew
Tower 5 Std. Dev. (45 pts.)	0.19	0.28	0.71	0.29	0.29	0.22
Tower 6 Std. Dev. (53 pts.)	0.16	0.06	0.06	0.07	0.07	0.11

TABLE 8
CTSA Accuracy for Vendor C Towers (°C)

CTSA	DOE2 V2.2	Merkel	NTU-Effectiveness	Feltzin	Exact	Cnew
Tower 7 Std. Dev. (84 pts.)	0.28	0.41	0.45	0.42	0.42	0.32
Tower 8 Std. Dev. (84 pts.)	0.46	0.29	0.60	0.28	0.28	0.34
Tower 9 Std. Dev. (83 pts.)	0.53	0.19	0.67	0.17	0.17	0.33

TABLE 9
CTSA Accuracy for Vendor D Cooling Towers (°C)

CTSA	DOE2 V2.2	Merkel	NTU-Effectiveness	Feltzin	Exact	Cnew
Tower 10B Std. Dev. (82 pts.)	0.43	0.37	0.96	0.31	0.31	0.32
Tower 11B Std. Dev. (96 pts.)	0.32	0.42	0.85	0.35	0.35	0.18
Tower 12B Std. Dev. (94 pts.)	0.62	0.57	0.83	0.54	0.54	0.29

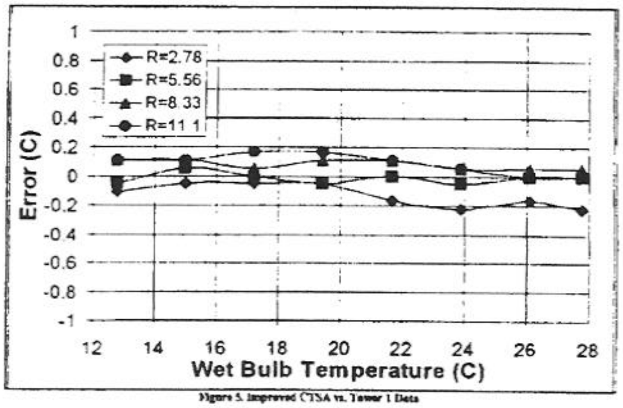

Figure 5 *Improved CTSA vs. tower 1 data.*

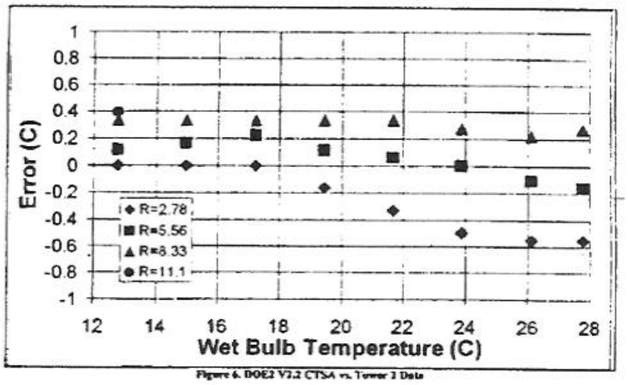

Figure 6 *DOE2 version 2.2 CTSA vs. tower 2 data.*

design point and provide a direct comparison between the two vendors.

Table 7 shows a comparison between towers 5 and 6. Towers 5 and 6 are a large-range/close-approach tower and a smaller-range/larger approach tower, respectively. This comparison suggests that like the analytical CTSAs, the new CTSA does a better job of predicting the performance of the small-range/large approach tower than the large-range/close-approach tower.

A comparison may be made among towers 7, 8 and 9, all vendor C towers with the same wet-bulb\approach\range design conditions but with increasing water flow, fan power, and heat load. This comparison, shown in Table 8, suggests that unlike the DOE2 version 2.2 CTSA, which provides

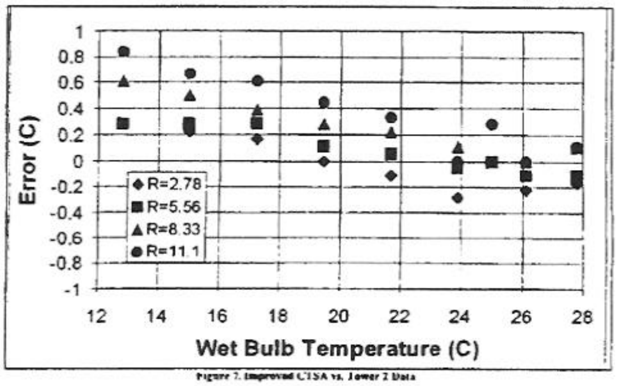

Figure 7 Improved CTSA vs. tower 2 data.

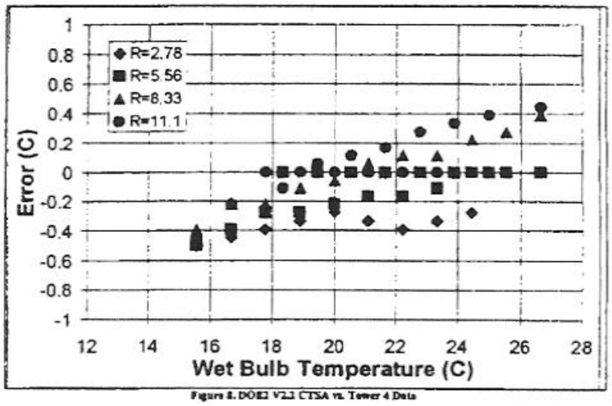

Figure 8 DOE2 version 2.2 CTSA vs. tower 4 data.

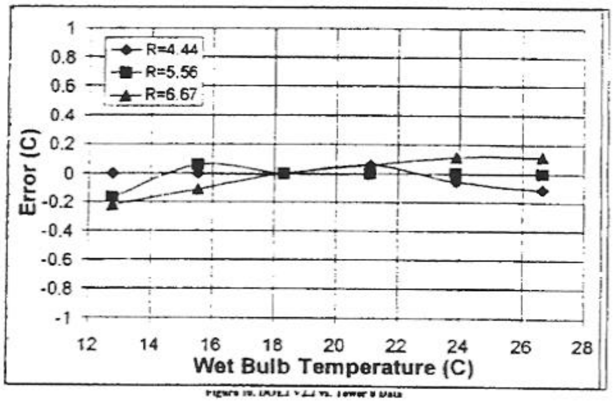

Figure 10 DOE2 version 2.2 CTSA vs. tower 8 data.

poorer correlations as heat load and fan power increase, the new CTSA provides consistent results independent of these parameters. Figure 9 shows that the new CTSA is well behaved for tower 8.

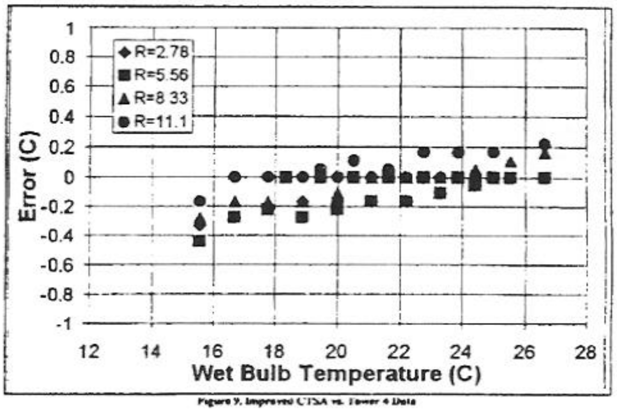

Figure 9 Improved CTSA vs. tower 4 data.

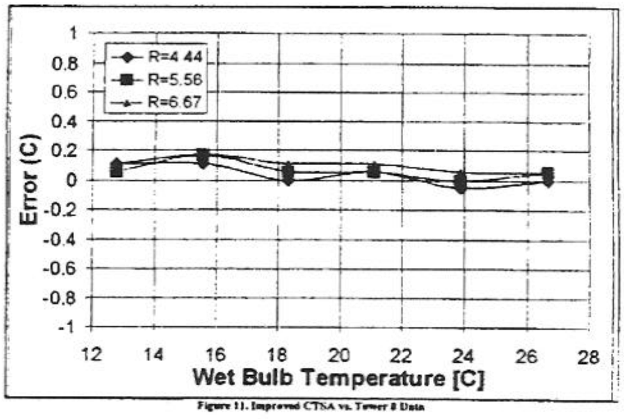

Figure 11 Improved CTSA vs. tower 8 data.

A comparison may be made among towers 10, 11, and 12, all vendor D towers with the same wet-bulb\approach\range design conditions and fan power but with decreasing water flow and heat load. Towers 10, 11, and 12 are physically identical, except for the fill. This comparison, shown in Table 9, suggests that the new CTSA more accurately predicts the performance of these towers than the other CTSAs.

DISCUSSION

For the span of flows, wet-bulb temperatures, cooling ranges, and approaches to wet-bulb temperature considered in this study, the maximum error in computed approach over the entire range of data was from 0.9°C to 2.2°C for all of the CTSAs except for the NTU-effectiveness CTSA. Differences exist among the CTSAs and between the empirical and the analytical CTSAs that are worth noting. For example, the analytical CTSAs require considerably more computational time. Somewhat surprisingly, all of the CTSAs appear to do a better job of predicting the performance of crossflow than counterflow towers. This may be due, in part, to the fact that the error appears to increase with increasing cooling range for counterflow towers. The empirical CTSAs appear to provide more consistent results over a wide span of cooling ranges than do the analytical CTSAs.

CONCLUSIONS

Care must be exercised in extrapolating the results beyond the range of flows, wet-bulb temperatures, cooling ranges, and approaches considered. Neither the empirical nor the analytical models considered appear to exhibit any particular advantage in extrapolating results beyond the range of available data.

The purely empirical CTSAs were shown to provide accuracy comparable to the analytical ones. In general, the new CTSAs are more accurate and better behaved than DOE2 version 2.2. This conclusion applies to both crossflow and counterflow cooling towers and to all of the cooling tower vendors. There are a few exceptions to this conclusion. For example, the error for the new CTSA is slightly higher than that of DOE2 version 2.2 for tower 5, and the new CTSA is not well behaved for tower 2. However, overall, the error for the new CTSA is approximately two-thirds that of DOE2 version 2.2.

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