THERMAL MODELING OF EVACUATED TUBULAR COLLECTORS

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ABSTRACT

An evacuated tubular collector (ETC) differs from the more common flat-plate collector in geometry, heat loss characteristics, and capacitance. In this paper, the effects of these differences on performance calculations are studied. Computed results are compared to measured performance data for two large ETC systems. Based on these comparisons, improvements to traditional collector modeling to best simulate ETCs are suggested.

1. INTRODUCTION

The objective of this study was to develop an ETC model which predicts collector array performance in reasonable agreement with measured performance. Operating data from two large ETC systems were used as simulation input and to compare predicted and measured performance. The collectors simulated are located at the Cherokee Indian Hospital (NC) and the Gainesville Job Corps Center (FL), both sites from the Solar in Federal Buildings Program (1, 2). The TRNSYS simulation program (3), is used and the traditional TRNSYS solar collector model is revised to improve the modeling of ETCs. The first question which is addressed is how well do conventional simulations, using only manufacturer's collector parameters and incidence angle modifiers and no adjustments for unique ETC properties such as high capacitance, predict collector performance. Then, the sensitivity of the ETC model predictions to various parameters is studied. Finally, conclusions are drawn about ETC modeling from the study and simulation of the Cherokee and Gainesville systems.

2. SIMULATION 3

Each of the SFBP quality sites was extensively instrumented by the Vitro Corporation to measure quantities such as temperatures and flow rates throughout the system. Data records, including the date, time, and desired sensor values, were stored for each 5 1/3 minute interval over the monitoring period. Six months of data are available for the Cherokee system and nine months for the Gainesville system. The following section describes some of the difficulties associated with using real data as simulation input.

A number of data records for the individual time steps were missing on both of the system data tapes. This presented a problem when using the data to drive simulations because TRNSYS requires that input values be supplied at constant intervals throughout the simulation period. Overall, approximately 12% of the Cherokee and 5% of the Gainesville data were not available. Many of the longer gaps, i.e. 5 hrs to 3 days in length, were documented in monitoring reports as missing maintenance or system failure. There were also many shorter data gaps, usually ranging from one to ten time steps. On screening the data, it was found that most of the gaps were either less than an hour or greater than three hours in length. The shorter gaps were filled with new records using interpolated values. Days with longer gaps were considered unsuitable for use as simulation input.

After filling gaps, all of the Cherokee and Gainesville data were plotted and visually screened to look for obvious problems with the sensor values and also to look at the weather conditions over any given period. Many miscellaneous problems were found. Sensor failures were obvious when a reading would suddenly change from a reasonable value to zero for a number of time steps. Collector controls clearly malfunctioned at times, and days with controllers errors were not used for simulation. After all of the data were screened, six two week periods from each month of data were chosen as simulation input for each of the two systems. Longer simulations were not feasible. For each two week period, simulations were run using each of the several models. The simulations were based on measured flow ratio and inlet temperatures. Outlet temperatures and collector gains were computed, for comparisons with measured collected energy and output temperature.

Comparisons of measured energy collection, $Q_{u,M}$ and simulated (predicted) energy collections, $Q_{u,T}$ are made in terms of a percent difference, which is defined as:

$$PD = \frac{Q_{u,T} - Q_{u,M}}{Q_{u,M}} \times 100\% \quad (1)$$

The bias error is also given which measures the average difference between the predicted outlet temperature $T_{o\ T}$, and measured outlet temperature at $T_{o,m}$ every time step. The bias error is given by:

$$BE = \frac{\sum_{i=1}^{n} \left(T_{o,M} - T_{o,T}\right)}{n} \quad (2)$$

Bias error represents an offset for the predicted results and if large it is usually an indication of a systematic problem with either the model or the measurements. (Due to sensor limitations, energy flow measurements are accurate to within 4% and temperature measurements to +/- 1 degree F).

Initial simulation results were obtained using the zero capacitance collector model and laboratory test values for collector performance parameters, $F_R(\tau\alpha)$ and $F_R U_L$, and incidence angle modifiers, $K_{\tau\alpha}$. Results of these simulations and comparisons with measurements are shown in Table 1.

Table 1: Initial Simulation Results

Month	$Q_{u,M}$ (total Btu x 10^6)	$Q_{u,T}$	BE (deg F)	PD %
CHEROKEE				
JAN	31.55	27.61	4.6	-12.5
FEB	33.76	32.55	5.0	-3.6
MAR	43.89	40.38	5.1	-8.0
APR	42.72	36.41	6.4	-14.8
GAINESVILLE				
APR	52.14	47.80	6.2	-8.3
JUN	48.72	40.14	5.6	-17.6
JUL	43.85	33.58	7.2	-23.4
SEP	29.37	22.26	9.9	-24.2
SUM	326.00	280.73	—	-13.8
Mean Bias Error = 6.3				

3. PERFORMANCE PARAMETERS $F_R(\tau\alpha)n$ AND $F_R U_L$

The steady state performance of a solar collector, in terms of efficiency, can be expressed by the Hottel-Whillier equation written as:

$$\eta = \frac{\dot{Q}_U}{A_c I_T} = F_R\left(\tau\alpha\right)_n K_{\tau\alpha} - F_R U_L \frac{T_i - T_a}{I_T} \quad (3)$$

where:

$\dot{Q}_u$ = rate of useful energy gain
A_c = collector area
F_R = collector heat removal factor.
I_T = solar radiation incident on the tilted surface
$(\tau\alpha)_n$ = the transmittance absorptance product incorporating the collector optical properties at normal incidence.
$K_{\tau\alpha}$ = incidence angle modifier.
U_L = overall collector heat losscoefficient.
T_i = inlet fluid temperature
T_a = ambient temperature

The parameters $F_R(\tau\alpha)_n$ and $F_R U_L$ are determined by the standard ASHRAE 93-77 test (4). Measured η is plotted vs. $(T_i - T_a)/I_r$, the operating point. When the testing is done with beam radiation at near normal incidence, $K_{\tau\alpha}$ is unity. If F_R, U_L, and $(\tau\alpha)_n$ are constants, the plot will show a straight line with the intercept $F_R(\tau\alpha)_n$ and the slope $-F_R U_L$. In general, ETC test curves have a lower intercept and flatter slope than do curves for flat plate collectors. The reported performance parameter values for the Sunpack ETC system in operation in Gainesville are $F_R(\tau\alpha)_n$ = 0.57 and $F_R U_L$ = 0.21 Btu/ft^2 F. A typical flat plate collector might have the values of 0.75 and 0.70 for the intercept and slope, respectively. The reported ASHRAE values of the test parameters $F_R(\tau\alpha)_n$ and $F_R U_L$ are usually used in the design and simulation of solar collectors. However, there is some uncertainty as to how well these parameters, determined under controlled laboratory conditions, represent the performance of operating evacuated tubular collectors.

To compare the measured versus design performance of the Cherokee and Gainesville systems, $F_R U_L$ and $F_R(\tau\alpha)_n$ were derived from system operating data. Plots of the instantaneous efficiency versus the operating point were generated from the actual data collected over the two week monitoring periods used for simulation, using data from time steps when beam radiations is at near normal incidence. Data were also eliminated if the collector pump had not been running continuously for the previous hour to minimize errors due to transient effects. A regression analysis was performed on the points generated to find the best linear fit and thus the slope and intercept values, $F_R(\tau\alpha)_n$ and $F_R U_L$.

The results obtained from the Cherokee system data are shown below in Table 2. The standard deviation and R^2 values for each of the fits are also listed.

Three trends are obvious from these results. First, $F_R(\tau\alpha)_n$ values do not vary greatly from the test results. Second, the loss coefficients are, in general, lower than the value from the ASHRAE test. Third, while the standard deviation from the fit is small, the R^2 values are extremely low. The parameter R^2 is defined as unity minus the ratio of the variance of the residuals to the variance of the data. Because this number is consistently very small, this indicates that the two variances are about the same. This means that the curve fit of the data is very close to the horizontal line that runs through the average y value of the points

Table 2: Calculated $F_R(\tau\alpha)_n$ and $F_R U_L$ (Btu/ft^2 F) for Cherokee simulation periods.

Month	$F_R (\tau\alpha)n$	$F_R U_L$	σ	R^2
JAN	0.359	0.087	0.041	0.017
FEB	0.410	0.201	0.097	0.098
MAR	0.398	0.102	0.043	0.083
APR	0.381	0.121	0.069	0.058
MAY	0.411	0.113	0.075	0.107
JUN	0.367	0.147	0.051	0.143
AVE	0.387	0.127	0.063	0.064
ASHRAE Test Values	0.391	0.224	—	—

regressed. While the low R^2 values would seem to indicate a poor fit, it is expected in this case because the slope of the predicted test curve line is so low. These results indicate, however, that using a simple average value for the collector efficiency may be as reasonable an approximation as the more complicated method of regression of the η vs $(T_i - T_a)/I_T$ points.

The same procedure was repeated using the Gainesville simulation data. The results are shown in Table 3.

Table 3: Calculated $F_R(\tau\alpha)_n$ and $F_R U_L$ (Btu/ft^2 F) for Gainesville simulation periods.

Month	$F_R (\tau\alpha)n$	$F_R U_L$	σ	R^2
APR	0.182	0.470	0.052	0.260
JUN	0.190	0.790	0.040	0.178
JUL	0.249	0.621	0.149	0.290
SEP	0.463	0.054	0.211	0.010
AVE	0.271	0.484	0.113	0.065
ASHRAE Test Values	0.486	-0.220	—	—

These data are not as consistent as the Cherokee data. The average standard deviation value is 0.125, compared to 0.072 for the Cherokee data. There are many possible reasons for this scatter. Some measurement error is likely, but the magnitude is difficult to estimate. Monitoring reports stated that there were problems with the inlet temperature sensor which was later replaced, although no details were given. The flow measurements used in the efficiency calculations were not as consistent as were the values for Cherokee, the measured flow rate fluctuated over about a 7 gpm range. This could indicate either inconsistent flow or measurement error; both problems would cause scatter in the efficiency plots. Because of the many problems associated with the values in Table 3, no attempts were made to use these parameters as collector inputs.

4. INCIDENCE ANGLE MODIFIERS

The incidence angle modifier, $K_{\tau\alpha}$, as used in equation 3, describes the dependence of the transmittance absorptance product on the angle of incidence. By definition,

$$K_{\tau\alpha} = \frac{(\tau\alpha)}{(\tau\alpha)_n} \tag{4}$$

As shown in Figure 1, longitudinal and transversal angles of incidence can be defined. Both sets of $K_{\tau\alpha}$ values are entered in TRNSYS in a user supplied data file containing between two and ten values of the incidence angle and the corresponding modifiers. The DSET Laboratories measured incidence angle modifiers of the O-I Sunpack ETC used in the Cherokee and Gainesville systems. Figure 2 shows the laboratory values for the transversal and longitudinal incidence angle modifiers (8). These $K_{\tau\alpha}$ values were used in TRNSYS for initial collector simulations. As a check, the outlet temperature error, defined as the difference between the simulated and measured value, was plotted as a function of transversal incidence angle for each time step over various days. Both collectors studied are south facing and mounted at a slope of about 30 degrees. Although the longitudinal angle of incidence varies seasonally, the longitudinal $K_{\tau\alpha}$ is very near unity for all angles encountered during operation. In general, there was a tendency of over prediction for angles above 70 degrees and under prediction in the 30 to 60 degree range for both of the systems.

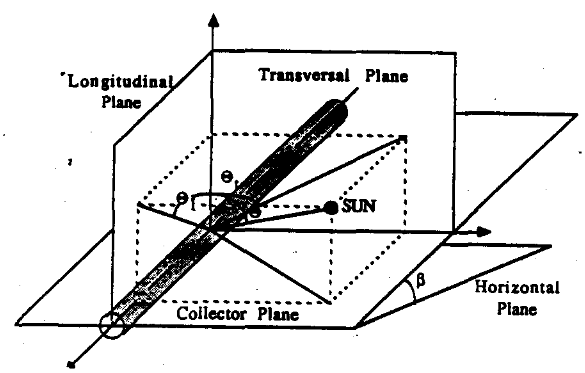

Fig. 1. Biaxial incidence angles for ETCs.

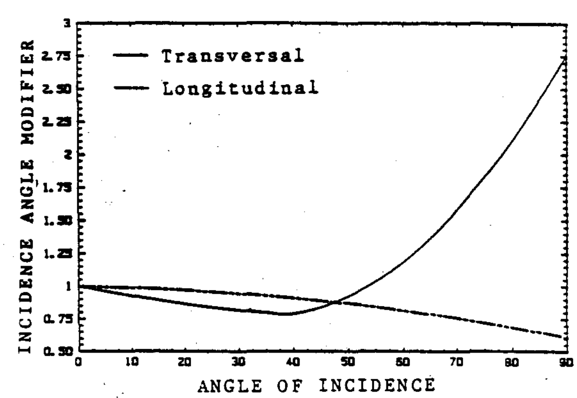

Fig. 2. DSET Lab incidence angle modifier curves for the Sunpack ETC.

This raises two questions: 1) How well do laboratory tests predict the actual tau-alpha dependence of collectors in operation? 2) How sensitive are simulation results to the values used, i.e. how much is the predicted performance affected by using a poor set of modifiers?

$K_{\tau\alpha}$ can be calculated from collector performance data by using the Hottel-Whillier equation and substituting the ASHRAE collector performance factors (experimentally determined from normal incidence data) and the measured performance. The instantaneous value of $K_{\tau\alpha}$ is defined by rearranging equation 3 and substituting the definition of $\dot{Q}_u$ to get:

$$K_{\tau\alpha} = \frac{\left[\frac{\dot{m}C_p(T_o - T_i)}{A_c I_T} + \frac{F_R U_L(T_i - T_a)}{A_c I_T}\right]}{F_R(\tau\alpha)_n} \quad (5)$$

$K_{\tau\alpha}$ was calculated at each time step and the corresponding incidence angles were calculated from the data, time of day, location, and collector orientation. Implicit in this calculation procedure is the assumption of linear behavior for the collector efficiency curve. The ASHRAE parameters $F_R(\tau\alpha)n$ and $F_R U_L$ were used. The values of $K_{\tau\alpha}$ were then plotted as a function of transversal incidence angle and fit with a third order regression routine. Table 4 shows the values obtained for both of the systems when simulation data from all of the periods were used in the calculation procedure.

Table 4: Transversal incidence angle modifier comparison for simulation data

Θt	0	10	20	30	40	50	60	70	80	90
Cherokee										
	1.0	1.02	1.04	1.09	1.17	1.26	1.35	1.43	1.48	1.50
Gainesville										
	1.0	.99	.96	.94	.94	.93	.96	1.02	1.10	1.20
DSET										
	1.1	.92	.86	.81	.80	.92	1.18	1.58	2.10	2.76
Lab Test										

Thus collector performance is overpredicted in the 30 to 50 degree range and underpredicted above 60 degrees if laboratory test data for $K_{\tau\alpha}$ are used. The simulations were repeated using the new $K_{\tau\alpha}$ values. The results are in Table 5.

The simulations were again repeated, but with no incidence angle modification by setting $K_{\tau\alpha}$ equal to unity for all angles. These results are shown in Table 6.

Simulation results using the calculated incidence angle modifiers improved 8.7% for the average energy collected percent difference and 1.3 degrees for the bias error compared to initial simulation results. For the no modification case, the percent difference improved 6.4% and the bias error was lowered .9 degrees.

Table 5: Simulation results using new $K_{\tau\alpha}$ values

Month	$Q_{u,M}$	$Q_{u,T}$	BE	PD
	(total Btu x 10^6)		(deg F)	(%)
CHEROKEE				
JAN	31.55	32.94	3.8	4.4
FEB	33.76	34.97	4.3	3.4
MAR	43.89	42.78	3.6	-2.5
APR	42.72	42.84	4.9	0.3
GAINESVILLE				
APR	52.14	50.84	5.0	-2.5
JUN	48.72	42.54	4.2	-12.7
JUL	43.85	37.37	5.7	-14.8
SEP	29.37	26.82	8.5	-8.7
SUM	326.00	311.08	—	-4.6
Mean Bias Error = 5.0				

Table 6: Simulation results using $K_{\tau\alpha}$ =1.0 for all angles

Month	$Q_{u,M}$	$Q_{u,T}$	BE	PD
	(total Btu x 10^6)		(deg F)	(%)
CHEROKEE				
JAN	31.55	29.46	4.7	-6.6
FEB	33.76	34.21	4.9	1.3
MAR	43.89	40.14	4.3	-8.5
APR	42.72	37.39	5.3	-12.5
GAINESVILLE				
APR	52.14	48.32	5.2	-7.3
JUN	48.72	44.41	4.2	-8.8
JUL	43.85	39.08	5.9	-10.9
SEP	29.37	27.87	8.6	-5.1
SUM	326.00	300.8	—	-7.7
Mean Bias Error = 5.4				

5. COLLECTOR CAPACITANCE

Many water heating ETCs have significantly higher capacitance than do flat-plate collectors due to their large volume of working fluid. The Sunpack model holds about 2.5 gallons of water in each collector, or about 1.5 lbs of fluid per square foot of collector area. This is about 5 times the typical value for a flat-plate collector. The effect of capacitance is a dampening of collector response to changes in input; it is characterized by the time constant, τ, the time required for a collector outlet fluid to attain 0.632 of the total change from its initial temperature to its ultimate steady state value after experiencing a step change in radiation or inlet temperature. Typical values for a flat-plate collector time constant are on the order of 1 to 2 minutes; the reported value for the Sunpack ETC is 21.07 minutes.

A new TRNSYS collector model including capacitance was developed, based on earlier work of Kummer (4). It combines a lumped parameter and a finite difference analysis. The collector is divided into a user specified number of nodes in the flow direction with each node having a fraction of the overall collector capacitance. The overall capacitance of a node is determined by combining that of the working fluid and the collector materials.

An energy balance on a single node, n, results in the following equations:

$$CAP_{eff}\,\frac{dT_n}{dt} = F'\left[S - U_L(T_n - T_a)\right] - \frac{\dot{m}C_p}{A_n}\left(T_{o,n} - T_{i,n}\right) \qquad (6)$$

where:

CAP_{eff} = effective capacitance per unit area

T_n = temperature of node

F' = collector efficiency factor

A_n = node collector area, A_c / total number of nodes

$T_{o,n}$ = fluid temperature leaving node n

$T_{i,n}$ = fluid temperature entering node n

The collector parameters are assumed to be constant. By writing energy balances on each node, a system of coupled, first order differential equations results. These equations are solved sequentially using the solution for the average temperature of node T_n as the inlet temperature for node T_{n+1}.

The value for effective capacitance is determined experimentally and then compared to hand calculations. This was done by comparing the simulated ETC response to a step change in radiation to the known capacitance behavior from the time constant test. Different values for the effective capacitance were substituted into the collector model until the system responded with the appropriate time constant for a 63.2% change from initial to steady state conditions. An effective capacitance value of 1.7 Btu/ft^2 F was determined from this experiment, which compared favorably with the value expected due to the water alone.

Also included in the model were the effects of filling and draining. This is needed to simulate the Cherokee collector system which has a drainback feature. Each night, the collector fluid is drained into a storage tank to prevent overnight heat loss and also as a freeze protection measure. When collector operation starts in the morning, the tubes fill up gradually over about fifteen minutes which results in a time dependent capacitance.

The use of the capacitance model improves the simulation results of both systems. The new model accounts for the long time constant of ETCs and the resulting delay of response to changes in input. Figure 3 shows an example of the outlet temperature response improvement for a two hour simulation of the Cherokee collector. The radiation over the period was fluctuating and the flow and inlet temperature were constant. The model also accounts for the morning filling of the Cherokee collectors and the morning heating of the non-draining Gainesville collector before operation is initiated. These effects are not seen with steady state calculations.

Table 7 shows simulation results using the multinode capacitance collector model with the laboratory test values for the collector parameters.

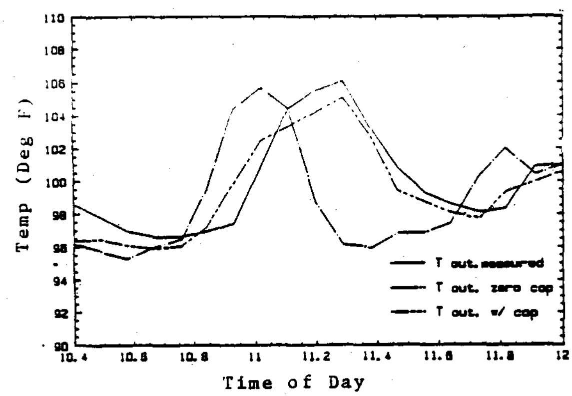

Fig. 3. Outlet temperature response improvement using the capacitance model.

Table 7: Simulation results using the multinode capacitance collector model

Month	$Q_{u,M}$	$Q_{u,T}$	BE	PD
	(total Btu x 10^6)		(deg F)	(%)
CHEROKEE				
JAN	31.55	30.03	3.4	-4.8
FEB	33.76	32.62	3.8	-3.7
MAR	43.89	42.01	4.5	-4.3
APR	42.72	40.16	5.3	-6.0
GAINESVILLE				
APR	52.14	49.36	5.6	-5.3
JUN	48.72	50.74	4.6	4.2
JUL	43.85	36.69	5.1	-16.6
SEP	29.37	27.69	8.1	-5.7
SUM	326.00	309.91	—	-4.9
Mean Bias Error = 5.1				

Finally, each simulation was repeated using the capacitance model and the calculated values for $F_R(\tau\alpha)_n$, F_RU_L, and $K_{\tau\alpha}$. These results are listed in Table 8.

Results using the capacitance model with design parameters improved 7.8 % for the energy collected accuracy and 1.2 degrees for the bias error. Using the capacitance models with calculated parameters, the respective improvements were 12.2% and 3.6 degrees.

Table 8: Simulation results using the multinode capacitance collector model and calculated collector parameters

Month	$Q_{u,M}$	$Q_{u,T}$	BE	PD
	(total Btu x 10^6)		(deg F)	(%)
CHEROKEE				
JAN	31.55	31.97	1.9	1.3
FEB	33.76	32.08	2.1	2.7
MAR	43.89	44.21	1.9	0.7
APR	42.72	43.43	3.2	1.7
GAINESVILLE				
APR	52.14	51.54	2.4	-1.1
JUN	48.72	48.85	2.2	0.3
JUL	43.85	40.09	2.3	5.1
SEP	29.37	28.90	6.1	-1.6
SUM	326.00	327.07	—	0.3
Mean Bias Error = 2.7				

6. CONCLUSIONS

The extensive instrumentation of the SFBP quality monitoring sites provides a means for analysis of component performance from various types of solar heating systems. However, the lack of details in the documentation of the monitoring presents problems when modeling systems, and the gaps in the data also present problems when using the data as simulation input. It was necessary to screen all data before use.

In general, the intercept $F_R(\tau\alpha)_n$ of the ASHRAE test curve (η vs. $(T_i - T_a)/I_T$) appears to be adequate for both systems studied. The laboratory determined F_RU_L, however is too high and tends to over estimate losses at high operating points. The monthly regression of the calculated test curve data for the Cherokee system supports the above conclusions. However, it is shown that the curve fit of the efficiency versus operating point data has a very low slope and is close to simply representing the average efficiency of the collector. Similar regressions for the Gainesville system were not conclusive due to the wide scatter of the data. Because simulation results using the best value of $F_R(\tau\alpha)_n$ and F_RU_L calculated from the data do not show great improvement over those using the ASHRAE test values, it is determined that the ASHRAE parameters are suitable for simulation input. No better estimations are available for design phase simulations.

The laboratory test values for the transversal incidence angle modifier for the Sunpack ETC were found to be unsatisfactory for simulation input for both of the systems studied. The $K_{\tau\alpha}$ curves generated form the measured operational data showed much less angular dependence than predicted. While the improvements using the calculated values are significant, it is important to note that the results were determined using the measured operational data. This information is obviously not available when design simulations for a system are performed. When no incidence angle modification was used, significant improvements over initial simulation were still achieved. Based on the results for the collectors studied, it appears that it is better to use no incidence angle modification, i.e. $K_{\tau\alpha}$ = 1 for all angles, when specific information about the test conditions and exact collector geometry is not known.

Use of the capacitance model results in improvement from better modeling of the initial daily operation for both of the systems because the new model accounts for the filling of the Cherokee array and for the morning heating of the Gainesville collector. Further improvement results from better temperature tracking throughout the day for both systems because the capacitance effects were accounted for. From the simulation results for the Gainesville and Cherokee collectors, it is evident that the capacitance model is needed in order to reproduce measured performance. In general, it is concluded that the capacitance model should be used to best simulate ETCs.

7. ACKNOWLEDGEMENT

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This paper discusses the simulation of evacuated tubular solar collectors (ETCs) for liquid heating. The application of traditional collector models and parameters for ETC modeling is studied. Specifically, four parameters are examined: collector capacitance, optical efficiency, thermal loss coefficients, and incidence angle modifiers. Each of these parameters is significantly different for ETCs than for flat plate collectors due to the geometry (including that of back reflectors), heat loss characteristics, and large volume of working fluid. The influence of these parameters on simulation results is studied through the use of TRNSYS. Measured data from two large ETC systems are used as inputs and for comparison of predicted and measured results. The systems modeled were at the Cherokee Indian Hospital, NC, and the Gainesville Job Corps Center, FL, both sites from the Solar in Federal Buildings Demonstration Program. From the behavior of the two systems studied, it is shown that it is necessary to include thermal capacitance in the model in order to reproduce the experimental results. It is also shown that for these two collectors, the dependence of performance on the incidence angle of beam radiation is much less than that predicted by laboratory tests. Furthermore, it is shown that the collector parameters $F_R(\tau\alpha)_n$ and F_RU_L as determined from the ASHRAE test are adequate as simulation input for ETCs modeled in this study.