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A GENERALIZED CORRELATION OF EXPERIMENTAL FLAT-PLATE COLLECTOR PERFORMANCE

by Frederick F. Simon and Dean R. Miller
Lewis Research Center
Cleveland, Ohio 44135

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ABSTRACT

A generalized correlation of flat-plate collector performance obtained by outdoor and indoor test methods is presented. This correlation shows that the indoor (simulator) test approach is a special case of the general situation of variable solar conditions. The important feature of the generalized correlation is that it permits a separation of the solar variables (flux, incident angle, etc.) which affect collector performance from the collector parameters (absorptance, transmittance, heat loss, etc.) which also affect collector performance and which are uniquely part of a given collector design.

The correlation permits an evaluation of the relative merits of using instantaneous, hourly and daily collector efficiencies in obtaining a good collector correlation. The question of the transient behavior outdoors of a collector is an important part of determining whether to use instantaneous, hourly or daily efficiency values in a correlation approach. Correlation of the experimental performance of collectors allows the following:

(a) Comparisons of different collector designs

(b) Collector performance prediction under conditions that differ from the conditions of the test program

(c) Monitoring performance degradation effects

INTRODUCTION

Performance testing of flat-plate solar collectors is an important part of the efforts to employ solar energy for the heating and cooling of buildings. Performance testing of collectors permits a determination

of the capability of a given collector to perform under variable solar flux and temperature conditions and gives the designer a basis for determining the size of a collector field for a given heating or cooling application. In addition, use of collector performance information with collector cost information permits an evaluation of collector merit from the point of view of cost effectiveness. Information relative to the life of a collector may also be obtained from a collector test program; however, this paper will concern itself only with collector performance testing. Specifically, this paper gives a basis for the correlation and interpretation of performance results obtained from outdoor or indoor collector tests.

The approach taken at the NASA-Lewis Research Center for determining collector performance is to test collectors under simulated (indoor) and actual (outdoor) conditions. Details of the test methods and test results are given in references 1 and 2. Figures 1 and 2 show the indoor and outdoor facilities, respectively. An important feature of any test program such as that of the NASA-LeRC, is the proper correlation of the collector performance test results. As explained in reference 3, a proper correlation allows one to differentiate between variables that govern collector performance (i.e., transmittance, absorptance, etc.) and the measured variables of solar flux, ambient temperature, wind speed, flow rate, etc. It was for the purpose of obtaining a good correlation that would give specific information on collector performance, that the authors of reference 3 made a case for testing under controlled, simulated conditions. An example of a correlation obtained with the simulator approach is given in figure 3. The collector efficiency axis intercept and slope of the correlation line plotted in figure 3 gives values which are a function of a given collector and which are essentially independent of the solar conditions (see ref. 3). Obtaining a correlation from outdoor tests as good as that of figure 3 is more difficult, due to variable weather and solar conditions. However, with sufficient care to take data obtained under fairly steady operating conditions, small solar incident angles and under clear skies, it is possible to obtain a correlation such as shown in figure 4.

The similarities between the correlations of figures 3 and 4 indicate that a more general correlation is in order. A correlation is needed which would account for such things as the angular response of the collector (due to changing sun positions), the amounts of diffuse and direct radiation, and instantaneous efficiency versus hourly or all-day collector efficiency. Such a general correlation would help determine the relative merits of using instantaneous, hourly, or all-day collector efficiency in collector performance correlations.

PROPOSED GENERAL CORRELATION

For the derivation of a generalized correlation, a designation is made as to mode of collector operation. Two modes of collector operation are considered: the test mode and the operational mode. In the test mode the collector heat transfer fluid is allowed to flow continuously throughout the day whether there is positive or negative energy collection. In the operational mode, the liquid flow through the collector is turned off when positive energy collection is not possible.

Test Mode - Derivation

The determination of steady-state or instantaneous efficiency by the use of simulator facility resulted, as given in reference 1, in the following collector performance equations:

$$\eta = a_\theta \left[K_{\alpha\tau} \frac{q_{dr}}{q_T} + \frac{q_{df}}{q_T} (1 + b_o) \right] - \frac{b_\theta (T_1 - T_a)}{q_T} \tag{1}$$

$$K_{\alpha\tau} = 1.0 + b_o \left(\frac{1}{\cos \theta_i} - 1 \right) \tag{2}$$

where

$$a_\theta = F_R(\alpha\tau)_{\theta_{i=o}}$$

and

$$b_\theta = F_R U_L$$

In equation (1), the coefficients a_θ and b_θ govern the amount of solar energy transmitted and absorbed and the amount of energy (radiant and convection) lost to the environment. These two coefficients and the angular response coefficient (b_o) are the key quantities to be obtained from any collector correlation.

For a known number (N) of instantaneous weather values obtained in any interval of time (t), the average collector efficiency ($\overline{\eta}_t$) is defined as

$$\overline{\eta}_t = \sum_1^N q_u \Big/ \sum_1^N q_T \tag{3}$$

The summation of the useful energy $\left(\sum_1^N q_u\right)$ obtained by the use of equation (1) is

$$\sum_1^N q_u = a_\theta \sum_1^N \left[K_{\alpha\tau} q_{dr} + (1 + b_o) q_{df}\right] - b_\theta \sum_1^N (T_1 - T_a) \tag{4}$$

which, upon substitution into equation (3) gives

$$\overline{\eta}_t = a_\theta \left[\frac{\sum_1^N K_{\alpha\tau} q_{dr}}{\sum_1^N q_T} + \frac{(1 + b_o) \sum_1^N q_{df}}{\sum_1^N q_T} \right] - \frac{b_\theta \sum_1^N (T_1 - T_a)}{\sum_1^N q_T} \tag{5}$$

Expressing the fraction of direct solar radiation as

$$R_t = \sum_1^N q_{dr} \Big/ \sum_1^N q_T \tag{6}$$

the diffuse fraction as

$$\frac{\sum_1^N q_{df}}{\sum_1^N q_T} = 1 - \frac{\sum_1^N q_{dr}}{\sum_1^N q_T} = 1 - R_t \tag{7}$$

the average total radiation flux for the time period in which N samples of the total flux were obtained as

$$\overline{q_{T,t}} = \frac{1}{N} \sum_1^N q_T \tag{8}$$

the average temperature difference as

$$\left(\overline{T_1 - T_a}\right)_t = \frac{1}{N} \sum_1^N (T_1 - T_a) \tag{9}$$

And defining an average incident angle modifier as

$$\overline{K_{\alpha\tau,t}} = \sum_{1}^{N} K_{\alpha\tau} q_{dr} \Big/ \sum_{1}^{N} q_{dr} \tag{10}$$

and substituting equations (6) to (10) into equation (5)

$$\overline{\eta}_t = a_\theta \left[\overline{K_{\alpha\tau,t}} R_t + (1 + b_o)(1 - R_t) \right] - \frac{b_\theta \left(\overline{T_1 - T_a} \right)_t}{\overline{q}_{T,t}} \tag{11}$$

Equation (11) is our general correlation equation for flat-plate collector performance. It can be further reduced to the form

$$\overline{\eta}_t^* = a_\theta - b_\theta \overline{\theta}_t^* \tag{12}$$

where

$$\overline{\eta}_t^* = \overline{\eta}_t / x \tag{12(a)}$$

$$x = \overline{K_{\alpha\tau,t}} R_t + (1 + b_o)(1 - R_t) \tag{12(b)}$$

$$\overline{\theta}_t^* = \overline{\theta}_t / x \tag{12(c)}$$

$$\overline{\theta}_t = \left(\overline{T_1 - T_a} \right)_t \Big/ \overline{q}_{T,t} \tag{12(d)}$$

Use of equation (12), allows us (in theory) to plot $\overline{\eta}_t^*$ against $\overline{\theta}_t^*$ and obtain the key collector parameters of a_θ and b_θ from the intercept and slope of the correlation line. For such a correlation to be properly obtained, it is assumed that conditions are such that the heat loss coefficient (U_L) is not affected very greatly by changes in ambient temperature and wind speed.

SIMPLIFIED VERSIONS OF GENERAL CORRELATIONS

Case I - Simulator Testing

In the case of testing with a simulator with no diffuse radiation, the value of x (eq. (12(b)) is equal to the incident angle modifier, $\overline{K_{\alpha\tau}}$ and the general correlation equation (11) reduces to

$$\overline{\eta}_t = a_\theta \overline{K_{\alpha\tau,t}} - \frac{b_\theta \left(\overline{T_1 - T_a}\right)_t}{\overline{q}_{T,t}} \tag{13}$$

or, using equation (12(d)) and recognizing that steady state, non-changing conditions exist

$$\eta = K_{\alpha\tau} a_\theta - b_\theta \theta \tag{14}$$

Case II - Clear Day For Small Solar Incident Angles

Most collectors have a value of the angular response coefficient (b_0) of around -0.2 and a value of the fraction of direct energy (R) for a clear (unpolluted) day of approximately 0.9. The incident angle modifier ($K_{\alpha\tau}$) for this case is essentially equal to one. Solving for x, (eq. (12(b)), yields an estimated value of 0.98. Using $x \simeq 1$ (discounting a two (2) percent possible error), the general correlation equation (11) reduces to

$$\overline{\eta}_t = a_\theta - \frac{b_\theta \left(\overline{T_1 - T_a}\right)_t}{\overline{q}_{T,t}} \tag{15}$$

or, using equation (12(d))

$$\overline{\eta}_t = a_\theta - b_\theta \overline{\theta}_t \tag{16}$$

Case III - Variable Sun Position - Variable Weather

A simplification for this case may be obtained by referring to equation (10) and defining a direct normal component of radiation

$$q_{dr} = q_{dr,n} \cos \theta_i \tag{17}$$

which upon substitution gives

$$\overline{K_{\alpha\tau,t}} = \frac{\sum_1^N K_{\alpha\tau} q_{dr,n} \cos \theta_i}{\sum_1^N q_{dr,n} \cos \theta_i} \tag{18}$$

Since the majority of solar energy collection occurs during the period of the day when the direct component of solar energy is very little affected by the sun's position, it is assumed that the direct normal component of radiation ($q_{dr,n}$) remains constant. Therefore,

$$\overline{K_{\alpha\tau,t}} = \frac{\sum_1^N K_{\alpha\tau} \cos \theta_i}{\sum_1^N \cos \theta_i} \tag{19}$$

Substituting equation (2) into equation (19) we obtain

$$\overline{K_{\alpha\tau,t}} = 1 + \frac{b_o \sum_1^N (1 - \cos\theta_i)}{\sum_1^N \cos\theta_i} \tag{20}$$

or

$$\overline{K_{\alpha\tau,t}} = 1 + b_o \left[\frac{N}{\sum_1^N \cos\theta_i} - 1.0 \right] \tag{21}$$

Defining

$$\overline{\cos\theta_i} = \frac{1}{N} \sum_1^N \cos\theta_i \tag{22}$$

and substituting equation (22) into (21), the average incident angle modifier is expressed as

$$\overline{K_{\alpha\tau,t}} = 1 + b_o \left(\frac{1}{\overline{\cos\theta_i}} - 1.0 \right) \tag{23}$$

Equations (23) and (12) are the simplified equations for Case III.

Case IV - All Day Collector Performance, Variable Weather Conditions

$$\theta_i = 90^o \rightarrow 0^o \rightarrow 90^o$$

The average incident angle modifier for this case is found from equation (23) to be

$$\overline{K_{\alpha\tau,t}} = 1 + b_o \tag{24}$$

Substituting equation (24) into the equation for x (eq. (12(b)) we find that for this case x has the following value

$$x = 1 + b_o \tag{25}$$

Thus, the correlating equation for Case IV becomes

$$\bar{\eta}_t = a_\theta(1 + b_o) - b_\theta \bar{\theta}_t \tag{26}$$

Operational Mode - Derivation

The basic difference between the derivation of the operational mode and the test mode is in that the summation quantities in the operational mode not include negative energy quantities. The result of this is to write equation (3) as

$$\bar{\eta}_o = \sum_1^{N_o} q_u \Big/ \sum_1^{N} q_T \tag{27}$$

and equation (4) as

$$\sum_1^{N_o} q_u = a_\theta \sum_1^{N_o} \left[K_{\alpha\tau} q_{dr} + (1 + b_o) q_{df}\right] - b_\theta \sum_1^{N_o} (T_1 - T_a) \tag{28}$$

where N_o represents all the collector performance values where the efficiency is greater than or equal to zero ($\eta \geq 0$).

Combining equations (27) and (28) the result is

$$\bar{\eta}_o = a_\theta \left[\frac{\sum_1^{N_o} K_{\alpha\tau} q_{dr}}{\sum_1^{N} q_T} + \frac{(1 + b_o) \sum_1^{N_o} q_{df}}{\sum_1^{N} q_T} \right] - \frac{b_\theta \sum_1^{N_o} (T_1 - T_a)}{\sum_1^{N} q_T} \tag{29}$$

Following the procedure for the test mode derivation we have

$$R_o = \sum_1^{N_o} q_{dr} \Big/ \sum_1^{N} q_T \tag{30}$$

$$\frac{\sum_1^{N_o} q_{df}}{\sum_1^{N} q_T} = 1 - \frac{\sum_1^{N_o} q_{dr}}{\sum_1^{N} q_T} = 1 - R_o \tag{31}$$

$$\bar{q}_{T,o} = \frac{1}{N_o} \sum_1^{N} q_T \tag{32}$$

$$\left(\overline{T_1 - T_a}\right)_o = \frac{1}{N_o} \sum_1^{N_o} (T_1 - T_a) \tag{33}$$

$$\overline{K_{\alpha\tau,o}} = \sum_{1}^{N_o} K_{\alpha\tau} q_{dr} \Big/ \sum_{1}^{N_o} q_{dr} \tag{34}$$

Substituting equations (30) to (34) into equation (29) the following basic equation is obtained:

$$\bar{\eta}_o = a_\theta \left[\overline{K_{\alpha\tau,o}} R_o + (1 + b_o)(1 - R_o) \right] - \frac{b_\theta \left(\overline{T_1 - T_a} \right)_o}{\bar{q}_{T,o}} \tag{35}$$

It should be noted that $\bar{q}_{T,o}$ (eq. (32)) is considered an average flux for the time period in which there is positive energy gain. Using the simplification of the test mode Case III, for the average incident angle modifier

$$\overline{K_{\alpha\tau,o}} = 1 + b_o \left(\frac{1}{\overline{\cos \theta_i}} - 1.0 \right) \tag{36}$$

where

$$\overline{\cos \theta_i} = \frac{1}{N_o} \sum_{1}^{N_o} \cos \theta_i \tag{37}$$

gives a simplified version of the general equation (eq. (35)).

Equation (35) may be used for correlating or predicting collector performance when a collector is run in an operational mode. This equation is especially useful for making calculations of collector performance over a given time period (hourly, daily, etc.) when information on solar weather and the collector parameters (a_θ and b_θ) are given.

CORRELATION EXAMPLE AND DISCUSSION

A check of the correlating equation (12) is made possible by using the results obtained from the collector testing program of the NASA-Lewis Research Center. The details of the test methods and apparatus are given in references 1 and 2 for the indoor and outdoor testing of solar collectors. Figure 5 presents the indoor and outdoor performance data for a black chrome - 2 glass collector in the format required by the correlation equation (eq. (12)). The first thing to be noted from figure 5 is that a general correlation does indeed exist for a wide range of variables. As an example of this, it is shown in figure 5 that the outdoor days went from clear days (R = 0.9) to cloudy days (R = 0.5).

Testing with a simulator can be considered a special case of the general correlation. One advantage of the simulator data is its simplicity since the standard "sun" gives essentially all direct radiation (R = 1) and the incident angle can be controlled (in this case $\theta_i = 0$).

The key advantage of obtaining a correlation such as shown in figure 5 is that it permits a determination of the key collector parameters. These parameters are obtainable from the intercept of the correlation ($a_\theta = F_R \alpha\tau$) and the slope of the correlation ($b_\theta = F_R U_L$). It should be noted that the constant a_θ is for a zero incident angle ($\theta_i = 0$). These parameters can be used for evaluation of collector design and for prediction of the collector performance under conditions not encountered in the original test program. An example of such a use is given by equation (35) for determining collector performance in an operating mode of an actual solar heating and/or cooling system.

The applicability of instantaneous efficiency data for correlation purposes is best demonstrated by a comparison of 16 minute averaged performance data and instantaneous performance data with the correlating line of figure 5. This comparison is shown in figures 6(a) and (b). Figures 6(a) and (b) demonstrate that the use of instantaneous data is not always recommended. This situation is more aggravated when we go to a truly instantaneous basis (fig. 6(b)) rather than the nearly instantaneous base of a 16 minute period (fig. 6(a)). However, the use

of clear day data with incident angles close to zero does permit the use of the same simplified correlation as used for the simulator data (see eq. (14) and Case II). This may be done if the collector time constant is approximately 10 minutes. However, if the collector time constant is in the order of 1 hour as reported in reference 1 for a tubular type of collector, then the use of hourly or daily efficiencies is recommended for a correlation basis. It should be clear upon inspection of figure 5 that the basis (hourly or daily) for collector efficiency does not appear to interfere with the collector correlation objectives of obtaining the key collector parameters (a_θ and b_θ).

One collector parameter which is a little difficult to obtain is the angular response constant (b_o). This constant may be obtained from basic information on the angular response of coatings and glazing materials or from controlled angular tests run with the simulator (ref. 1). In any case by plotting the results as shown in figure 7, it is possible to use the slope of the line to obtain the angular response constant. Figure 7 shows that the angular response of collectors may not always be as expected (i.e., negative). Another way of possibly determining the angular response coefficient is to run full day collector performance ($\theta_i = 90^o \rightarrow 0^o \rightarrow 90^o$) and plot the data as indicated by equation (26). Thus, the intercept value of the correlation includes the angular response constant (intercept = $a_\theta(1 + b_o)$), and in using this intercept with the intercept obtained from the generalized correlation (a_θ), the angular response coefficient can be calculated.

CONCLUSIONS

A generalized collector performance correlation has been derived and shown by experimental verification to be of the proper form to account for the majority of the variable conditions encountered both in outdoor and in indoor collector tests. This correlation permits a determination of collector parameters which are essentially nonvarying under conditions which do vary randomly (outdoors) or conditions which vary in a controlled manner (indoors - simulator).

The use of instantaneous or near-instantaneous collector performance data obtained outdoors is not always recommended - unless such data are obtained under clear day, steady conditions. Where variable solar conditions exist, it is recommended that hourly efficiencies be used for correlation purposes. Collectors with large time constants may even require all-day efficiency values for correlation purposes.

The solar simulator approach is a simplified and special case of the more general situation of variable solar and weather conditions.

SYMBOLS

a_θ	collector performance constant, dimensionless
b_θ	collector performance constant, dimensionless
b_o	angular response constant, dimensionless
F_R	collector plate heat-removal efficiency, dimensionless
$K_{\alpha\tau}$	incident angle modifier, dimensionless
q_{df}	incident diffuse solar radiation, Btu/hr-ft^2, in plane of collector
q_{dr}	incident direct solar radiation, Btu/hr-ft^2, in plane of collector
q_T	total solar radiation, Btu/hr-ft^2, in plane of collector
q_u	useful energy collected, Btu/hr-ft^2
N	number of instantaneous data values
T_a	ambient temperature, ^oF
T_1	fluid inlet temperature, ^oF
U_L	overall collector heat loss coefficient, Btu/hr-ft^2, ^oF
α	collector surface absorptance, dimensionless
η	collector efficiency, dimensionless
τ	effective transmittance
θ_i	solar incident angle, degrees

Subscripts:

t test mode

o operational mode

n normal incidence

Superscript:

$\bar{}$ average conditions

REFERENCES

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2. Vernon, R. W., "Solar Collector Performance Evaluated Outdoors at NASA-Lewis Research Center," paper presented at NSF/RANN Workshop on Solar Collectors for Heating and Cooling Buildings., New York, New York, Nov. 21-23, 1974.

3. Simon, F. F. and Harlamert, P., "Flat-Plate Collector Performance Evaluation: The Case for a Solar Simulation Approach," International Solar Energy Society Annual Meeting, International Solar Energy Society, Cleveland, Ohio, 1973.

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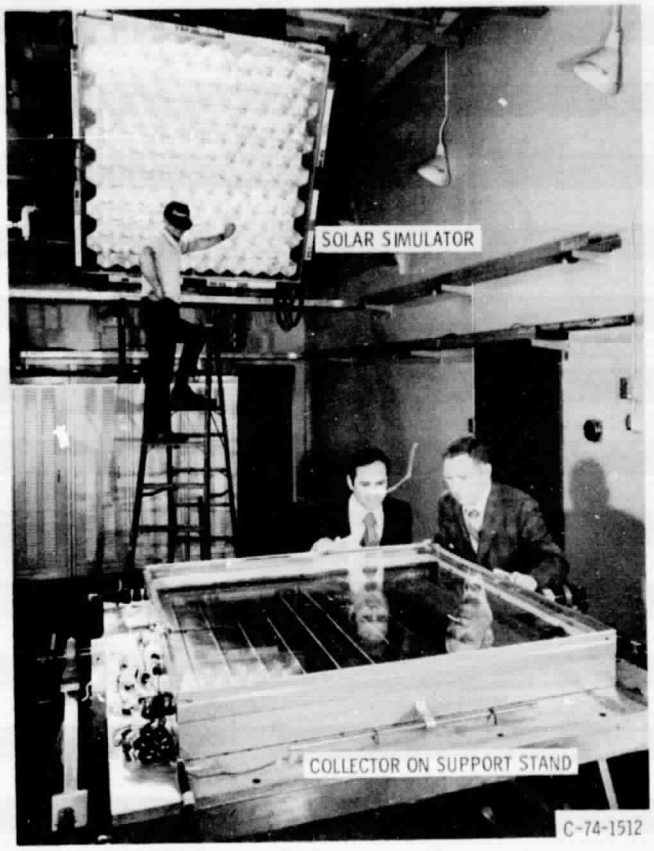

Figure 1. - Indoor facility used to experimentally determine solar collector performance.

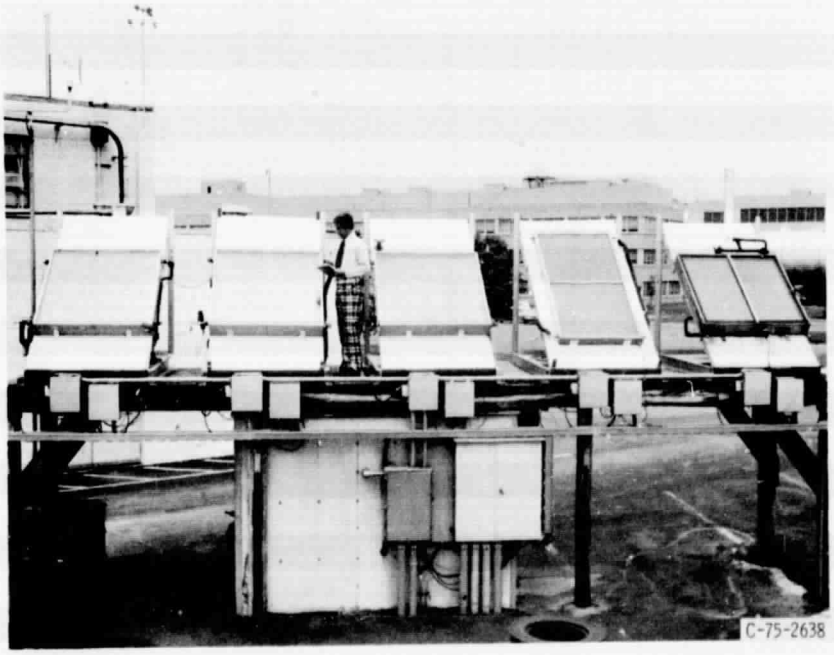

Figure 2. - Outdoor solar collector test facility.

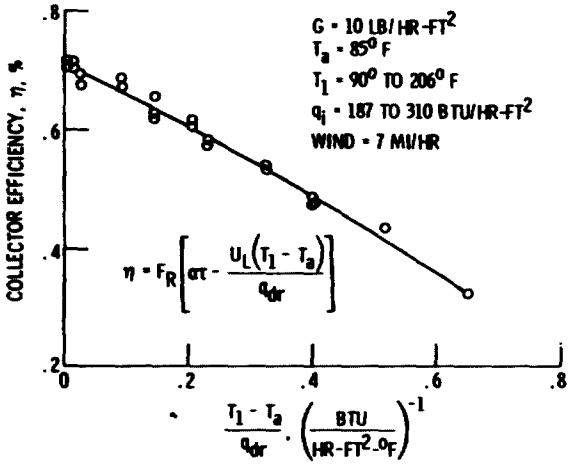

Figure 3. - Indoor (simulator) collector performance (black nickel, 2 glass collector).

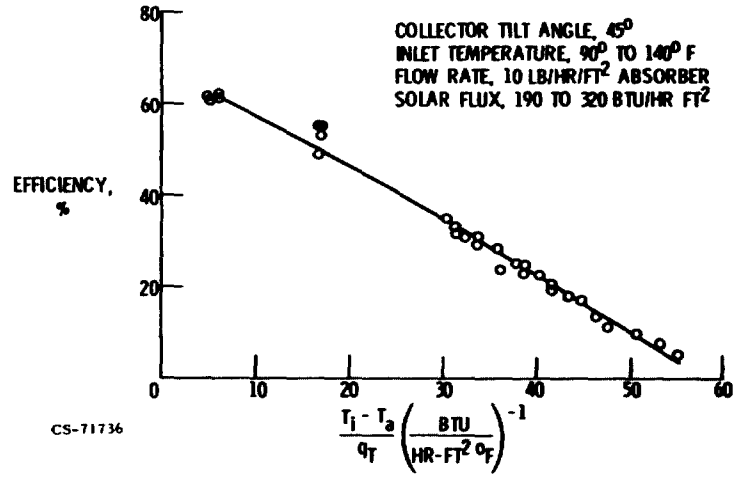

Figure 4. - Outdoor collector performance (ref. 2) (black paint, 2 glass collector).

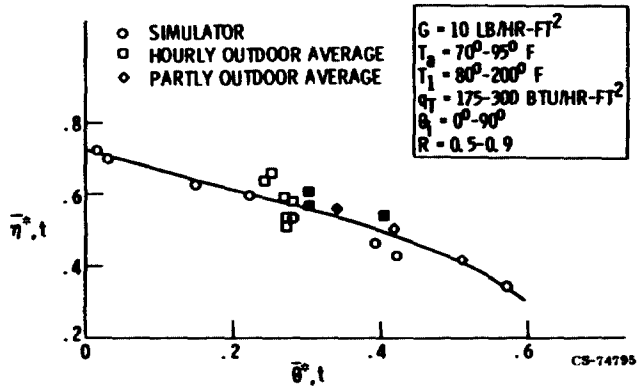

Figure 5. - Generalized correlation for a black chrome - 2 glass collector based on hourly and daily averages of clear and cloudy days.

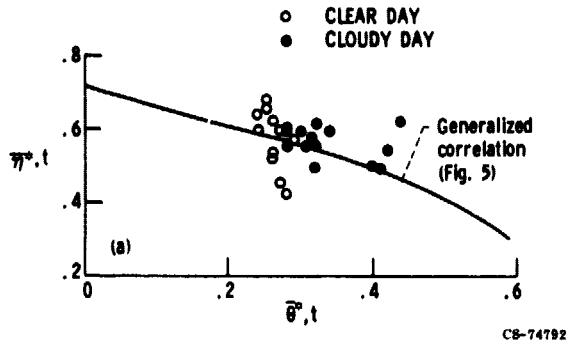

Figure 6. - Comparison of 16 minute averaged collector performance with generalized correlation.

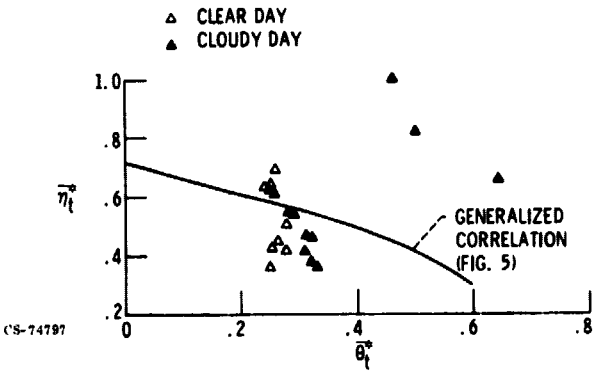

Figure 6(b). - Comparison of instantaneous collector performance with generalized correlation.

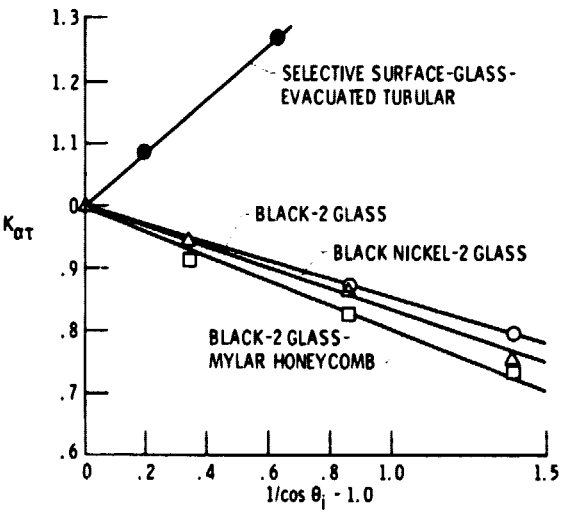

Figure 7. - Correlation of incident angle modifier (ref. 1).

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