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An analytical study on the thermal characteristics of flat-plate and evacuated solar collectors

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Abstract

In this study, we highlighted differences in the standards used in performance tests of solar collectors. We analyzed testing results for different types of solar collectors to determine the effects of the collector area and mass flow rate, which were not necessarily consistent across all tests. Our analysis showed that the factor, $F'(\tau\alpha)$, including collector efficiency factor (F'), could be correlated with the flow rate or area regardless of the collector type. Moreover, the collector loss coefficient ($F'U_L$) per flow rate or area for an evacuated collector was less that of a flat-plate collector; this was also correlated with the flow rate or area, regardless of the type of evacuated collector. As a result of this analysis, we propose a modified heat loss coefficient that includes the effects of all parameters that can be considered in a performance test and show that this coefficient could better describe the thermal characteristics of various types of solar collectors.

Keywords: Solar collector; Flat-plate collector; Evacuated collector; Collector heat-removal factor; Collector performance

1. Introduction

Under steady-state conditions, the useful heat gain obtained from a solar collector can be evaluated as the difference between the absorbed solar radiation and the thermal loss by using a heat removal factor:

$$Q_u = A_c F_R G_T(\tau\alpha) - A_c F_R U_L(T_i - T_a) = \dot{m} C_p(T_o - T_i) , \quad (1)$$

$$Q_u = A_c F' G_T(\tau\alpha) - A_c F' U_L(T_m - T_a) . \quad (2)$$

A measure of the collector performance is typically referred to as the collector efficiency, defined as the ratio of the useful gain to the incident solar energy:

$$\eta = \frac{Q_u}{A_c G_T} = F_R(\tau\alpha) - F_R U_L \frac{(T_i - T_a)}{G_T} = \eta_o - F_R U_L \frac{(T_i - T_a)}{G_T} \quad (3)$$

$$\eta = \frac{Q_u}{A_c G_T} = F'(\tau\alpha) - F' U_L \frac{(T_m - T_a)}{G_T} = \eta_o - F' U_L \frac{(T_m - T_a)}{G_T} \quad (4)$$

Marschall and Adams [1] introduced the concept of collector efficiency as a first step in estimating the maximum heat gain of a solar collector using the gain of potential work per unit time through a first and second law analysis. They showed that the collector efficiency and other environmental or operational parameters could easily be established. Gordon [2] analyzed the effects of the nonlinear heat loss coefficient in flat-plate collector efficiency curves, while Hahne [3] numerically demonstrated the effects of the coefficient on the efficiency of several designs and test parameters for various types of flat-plate solar collectors. Many other studies have examined the performance characteristics of various types of solar collectors, but these have usually been confined to just the collector efficiency shown in Eqs. (3) and (4).

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Manufacturers generally wish to know the efficiency of their solar collectors for various inlet temperatures with a fixed mass flow rate. Testing institutes such as the Solartechnik Prüfung Forschung (SPF) in Switzerland, the Institut für Thermodynamik und Wärmetechnik (ITW) in Germany, and the Korea Institute of Energy Research (KIER) perform thermal tests on collectors. They quote collector performance in the form of a curve produced by curve-fitting Eqs. (3) or (4) on a graph of η versus $(T_i - T_a)/G_T$ or $(T_m - T_a)/G_T$. This determines the four constants $F_R(\tau\ \alpha)$, F_RU_L, $F'(\tau\ \alpha)$, and $F'U_L$.

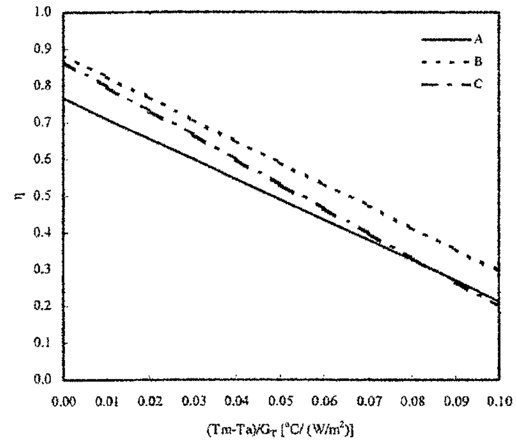
However, the useful heat gain varies with different mass flow rates for a given collector, which means that the collector efficiency also varies. Hahne [3] showed that the efficiency curves were a function of the flow rate, and obtained different curves for various collector areas using the same mass flow rate. Therefore, the four constants of $F_R(\tau\ \alpha)$, F_RU_L, $F'(\tau\ \alpha)$, and $F'U_L$ determined through the performance test could directly characterize the thermal properties of solar collectors.

The first objective of this study was to determine a single new parameter that would better describe the performance of a solar collector. The second objective was to compare the differences among the solar collector efficiencies measured by the SPF, ITW, and KIER.

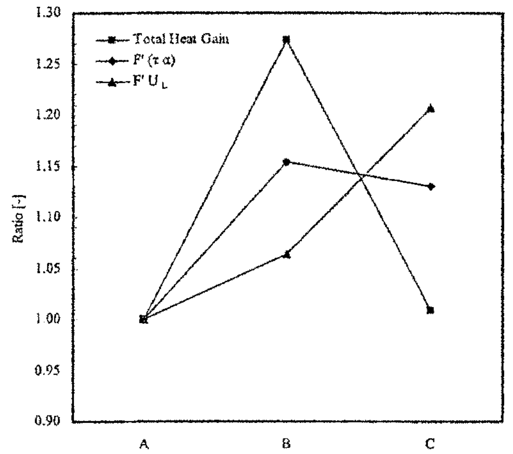
2. Analytical study

2.1. Requirement for a new parameter

When a solar collector is selected for a specific application, the first point of reference is the efficiency curve and total heat gain for each collector. Fig. 1(a) is based on real data from performance tests of three flat-plate solar collectors manufactured by Korean manufacturers A, B, and C. Each collector had a different collector area. The flow rates for those collectors, 0.02 kg/s per unit collector surface area (aperture area), were different depending on the Korean Industrial Standard (KS standard). However, Fig. 1(a) does not lend itself to the easy or intuitive estimation of the relation between $F'(\tau\ \alpha)$ (or $F'U_L$) and the total heat gain. This carries through to Fig. 1(b), where the ratio is calculated by using manufacturer A's product as a baseline for values of $F'(\tau\ \alpha)$, $F'U_L$, and the total heat gain. It is difficult to determine a correlation between the efficiency curves and the total heat gain. Details of the three different solar collectors are given in Table 1.



(a) Efficiency characteristics of the three collectors



(b) Total heat gain ratio vs. efficiency parameters ratio for the three collectors

Fig. 1. Underlying concept.

Table 1. Physical characteristics and test conditions for the three collectors.

Makers	A	B	C
Aperture area [m²]	1.93	1.87	2.00
Flow rate [ℓ/hr]	138	136	150
Total heat gain [kcal]	1334	1699	1344
F' (τ α) [-]	0.766	0.884	0.866
F' U_L [W/(m²K)]	5.521	5.871	6.664

Moreover, to clearly show the necessity of the first objective, the effects of collector aperture area and flow rate should be roughly estimated.

The performance of a solar collector can be typically influenced by both the aperture area and the flow rate. To consider these variables simultaneously, we selected a characteristic parameter based on a simple solar collector efficiency analysis, defined as the flow rate divided by the aperture area. To better explain the basis for this, consider four cases. Case 1 has a unit area and flow rate. Case 2 has twice the area and twice the flow rate of Case 1. Case 3 has twice the area but the same flow rate as Case 1, while Case 4 has twice the flow rate but the same area as Case 1. Then the efficiencies of Cases 1 and 2 will be similar. The efficiency of Case 3 will be less than that of Case 1, and the efficiency of Case 4 will be greater than that of Case 1. Therefore, the efficiency of each case may be described as the flow rate divided by the area, as listed in Table 2, and this characteristic parameter makes sense quantitatively.

2.2 Standard comparison

The ITW, SPF, and KIER use test standards DIN-4795 [4], EN-12975 [5], and KS-R-ISO-9806-3[6], respectively, in their performance tests of solar collectors. The three standards follow roughly the same procedure and method with the exceptions listed in Table 3. The ITW and SPF standards do not specify the mass flow rate, whereas the KIER standard specifies a rate of 0.02 kg/s per unit of the collector surface area, except for special cases identified by the manufacturers.

Table 2. Estimation of the relationship between the efficiency and test conditions.

Institute	ITW	SPF	KIER
Standard	DIN 4795	EN 12975	KS 9806
Working fluid	Water	Water/glycol	Water
Flow rate [kg/s m^2]	not specified	not specified	0.02
Global irradiance [W/m^2]	up to 600	up to 700	up to 700
Ambient temperature variation during test	within ±0.5K	within ±1.0K	within ±1.0K

Table 3. Comparison of the standards used by each institute.

Institute	ITW	SPF	KIER
Standard	DIN 4795	EN 12975	KS 9806
Working fluid	Water	Water/glycol	Water
Flow rate [kg/s m^2]	not specified	not specified	0.02
Global irradiance [W/m^2]	up to 600	up to 700	up to 700
Ambient temperature variation during test	within ±0.5K	within ±1.0K	within ±1.0K

SPF evaluates the performance of a solar collector by using the equation

$$\eta = \eta_o - a_1 T_m^* - a_2 G_T T_m^{*2} . \quad (5)$$

The temperature difference is defined as

$$T_m^* = \frac{T_m - T_a}{G_T} , \quad (6)$$

$$\text{where } T_m = \frac{T_i + T_o}{2} . \quad (7)$$

When Eq. (6) is substituted into Eq. (5), the efficiency equation becomes

$$\begin{aligned} \eta &= \eta_o - a_1 \frac{T_m - T_a}{G_T} - a_2 G_T \left(\frac{T_m - T_a}{G_T} \right)^2 \\ &= \eta_o - a_1 \frac{T_m - T_a}{G_T} - a_2 \frac{(T_m - T_a)^2}{G_T} \end{aligned} . \quad (8)$$

ITW measures the collector efficiency as

$$\eta = \eta_o - k_1 \frac{T_m - T_a}{G_T} - k_2 \frac{(T_m - T_a)^2}{G_T} , \quad (9)$$

which is essentially the same relationship used by SPF. By writing the efficiency as

$$\eta = F'(\tau\alpha) - F' U_L \frac{T_m - T_a}{G_T} \quad (10)$$

and using a correlation for U_L that was proposed by Cooper and Dunkle [7],

$$U_L = a + b(T_m - T_a) , \quad (11)$$

the efficiency equation becomes

$$\eta = F'(\tau\alpha) - F' a \frac{T_m - T_a}{G_T} - F' b \frac{(T_m - T_a)^2}{G_T} . \quad (12)$$

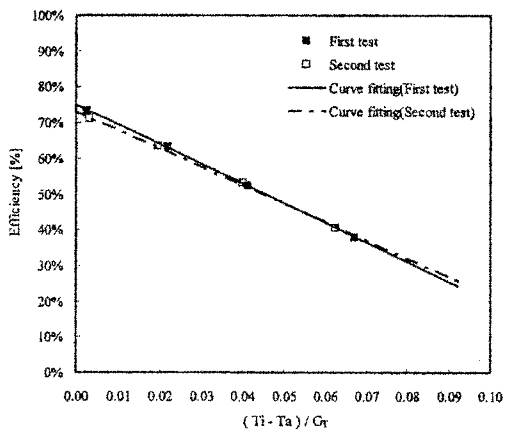
The relationships between the coefficients in the two methods are

$$a_1 = k_1 = F' \ a, \ a_2 = k_2 = F' \ b . \quad (13)$$

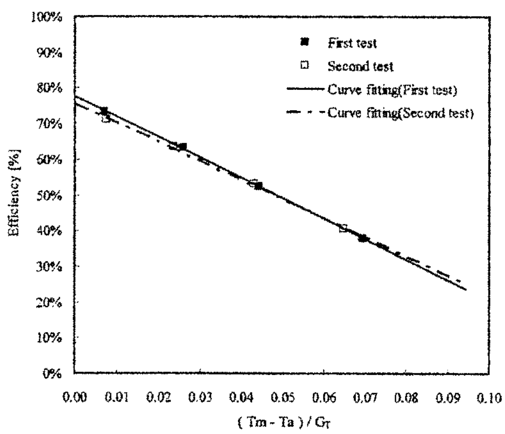
KIER uses a different method to obtain the collector efficiency based on general solar energy textbooks:

$$\eta = F_R(\tau\alpha) - F_R U_L \frac{T_i - T_a}{G_T}. \quad (14)$$

The methods used by the ITW and SPF to measure collector efficiencies have an outwardly independent variable with first- and second-order differences between the mean fluid temperature and the ambient temperature; this is used as the temperature potential. Because the fundamental relationships of the collector efficiencies are correlated with the independent variables by using a temperature potential over global irradiance, Eqs. (8) and (9) are not quadratic functions. Instead, they are three-dimensional polynomial equations that can be simplified into linear equations of the form $z = a + bx + cy$, where x is $(T_m - T_a)/G_T$ and y is $(T_m - T_a)^2/G_T$.



(a) Base inlet fluid temperature



(b) Base mean temperature

Fig. 2. The efficiency characteristics of a flat-plate collector performed by the KIER.

Fig. 2 shows the efficiency curves as linear equations curve-fitted for two collector performance tests conducted by the KIER on a single solar collector. Fig. 2(a) gives the efficiency versus $(T_i - T_a)/G_T$, using an x-axis scale based on the standard KIER reference. The curve-fitted equations were

$$\eta = 0.7504 - 5.5069 \frac{T_i - T_a}{G_T} \text{ and} \quad (15a)$$

$$\eta = 0.7327 - 5.1739 \frac{T_i - T_a}{G_T} \quad (15b)$$

for the first and second tests, respectively. When the temperature potential was based on the mean temperature T_m rather than the inlet temperature T_i as shown in Fig. 2(b), these equations became

$$\eta = 0.7763 - 5.6985 \frac{T_m - T_a}{G_T} \text{ and} \quad (16a)$$

$$\eta = 0.7564 - 5.3433 \frac{T_m - T_a}{G_T}. \quad (16b)$$

When the temperature potential was changed from the inlet value to the mean value, $F_R(\tau\alpha)$, $F'(\tau\alpha)$, $F_R U_L$, and $F'U_L$, as well as the y-axis intercept η_0, increased by 3.5%, similar to Eqs. (15) and (16).

For the SPF or ITW methods, the same test results gave

$$\eta = 0.7730 - 5.4360 \frac{T_m - T_a}{G_T} - 0.003626 \frac{(T_m - T_a)^2}{G_T}$$

and (17a)

$$\eta = 0.7463 - 4.5020 \frac{T_m - T_a}{G_T} - 0.01189 \frac{(T_m - T_a)^2}{G_T}. \quad (17b)$$

These appropriate coefficients for these equations were determined by using the least squares method. After the third (second-order) term in the right-hand side of Eq. (17) is omitted, a comparison of Eqs. (15) and (17) shows that the y-axis intercept η_0 increased from 2 to 3%, while $F_R U_L$, $F'U_L$, and $F'a$ decreased from 1 to 13%. All the performance test results obtained with the KIER method showed similar differences. Therefore, the exact relationship used to describe the performance of the solar collector is very important for the manufacturers.

For further analysis, we chose Eq. (10) as the reference efficiency equation, and curve-fitted the results for the SPF, ITW, and KIER methods. These three institutes have conducted numerous performance tests at various flow rates involving various types of solar collectors, including flat-plate, single-evacuated, and double-evacuated collectors with compound parabolic concentrators (CPCs) or mirrors. The maximum curve-fitting error was within 2% except in two cases that had an error of about 4%. Fig. 3 shows the range of collector areas (identified as aperture areas in the figure) that were tested and the volume flow rates supplied during these tests. A direct comparison is difficult for all the results in the figure because the efficiency differs with the flow rate for a given collector area.

To illustrate the performance characteristics of all the solar collectors on one plot, the data were converted to the efficiency expressed by Eq. (10). Fig. 4 shows $F'(\tau\alpha)$ and $F'U_L$ as functions of efficiency. $F'(\tau\alpha)$ ranged from 0.6 to 0.9, regardless of the type of solar collector, while $F'U_L$ of the flat-plate collector ranged from 3.8 to 11.8, greater than that of the evacuated collector, which ranged from 1.2 to 2.8. However, since this was for different applied flow rates and different aperture areas, it was not a clear comparison of the solar collector characteristics.

Fig. 5 gives $F'(\tau\alpha)$ and $F'U_L$ for various aperture areas, while Fig. 6 shows $F'(\tau\alpha)$ and $F'U_L$ for various volume flow rates. However, the physical significance of $F'(\tau\alpha)$ and $F'U_L$ is not evident from these plots due to the different conditions used for the tests, as described above.

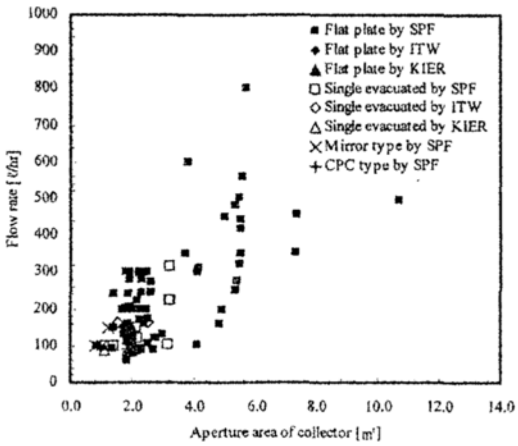


Fig. 3. The range in collector area and mass flow rate.

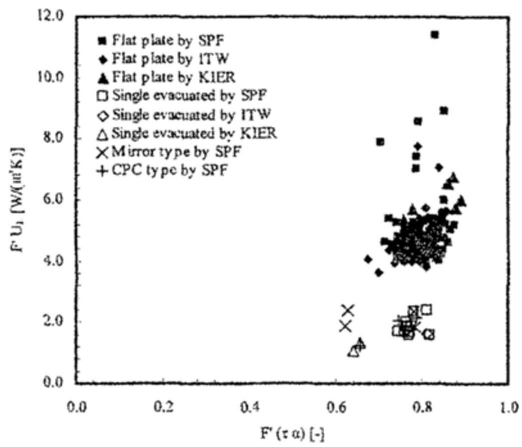


Fig. 4. The characteristics of $F'(\tau\alpha)$ and $F'U_L$.

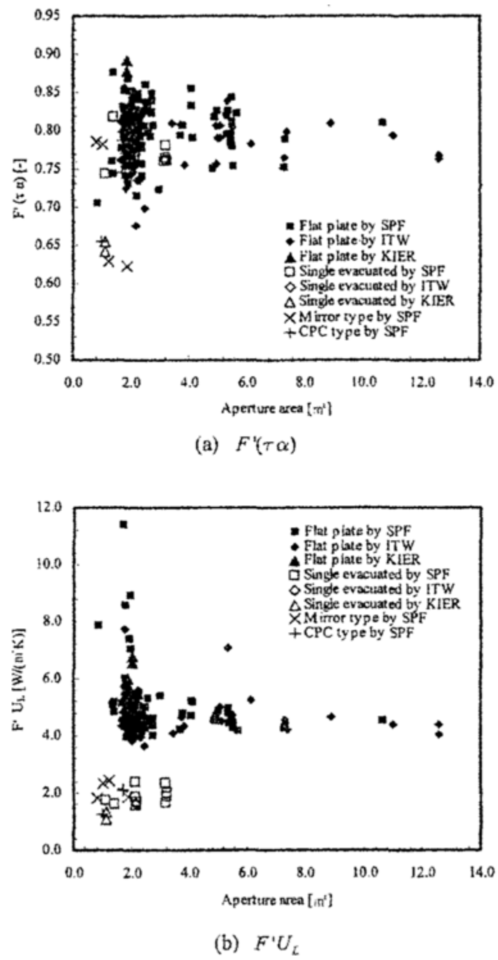
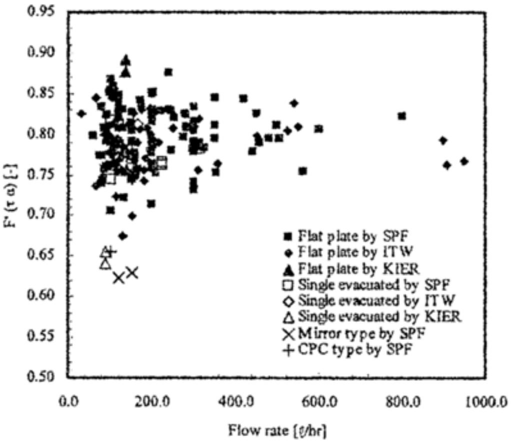
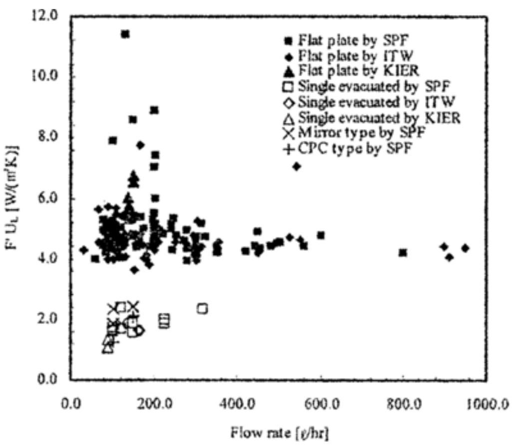


Fig. 5. The characteristics of performance based on the aperture area of the solar collector tested.



(a) $F'(\tau\alpha)$



(b) $F'U_L$

Fig. 6. The characteristics of performance based on the volume flow rate applied in the test.

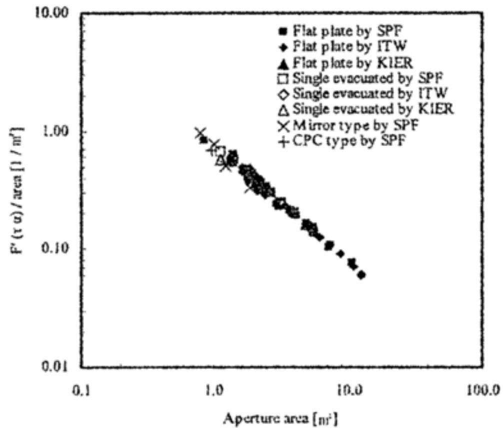
2.3 Theoretical analysis

The first objective of this study was to determine a single new parameter that would better describe the performance of a solar collector. To this end, we first examined the values of (F_RU_L), $F_R(\tau\alpha)$, $(F'U_L)$, and $F'(\tau\alpha)$ acquired under different flow rates and collector aperture areas. It was necessary to normalize these to compare them.

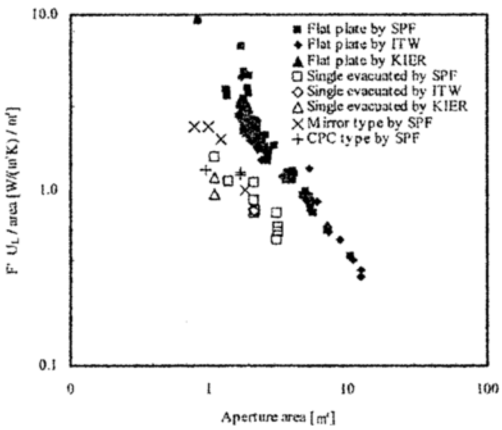
We examined the results of tests conducted at the SPF, ITW, and KIER using different applied flow rates. Since different efficiency equations were also used in these tests, we recomputed the results using Eq. (4) as the reference equation. Table 4 shows the number of tests performed by each institute and the type of solar collector examined.

Table 4. Number of test results used in this study.

Type \ Institute	SPF	ITW	KIER
Flat-plate	120	63	6
Single evacuated	10	2	2
Double evacuated with mirror	7	-	-
Double evacuated with CPC	3	-	-



(a) $F'(\tau\alpha)$

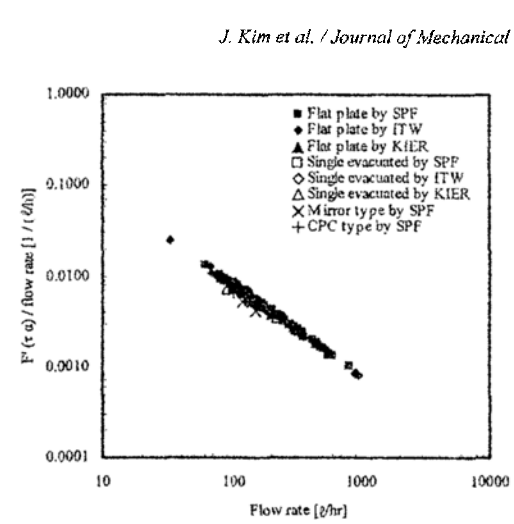


(b) $F'U_L$

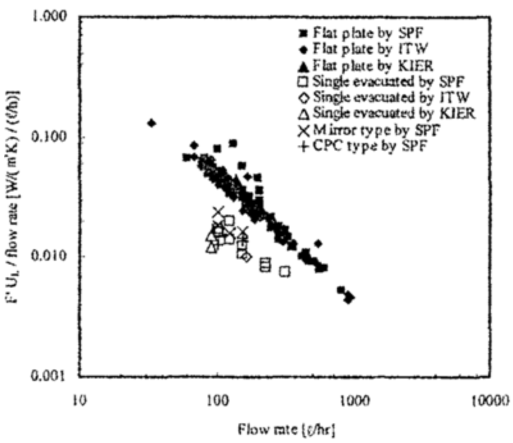
Fig. 7. The characteristics of performance based on the unit area.

3. Results and discussion

Fig. 7 shows $F'(\tau\alpha)$ and $F'U_L$ normalized to the aperture area of the solar collectors while Fig. 8 gives the same characteristics normalized to the volume flow rate applied during the performance tests. These figures clearly illustrate the physical significance of

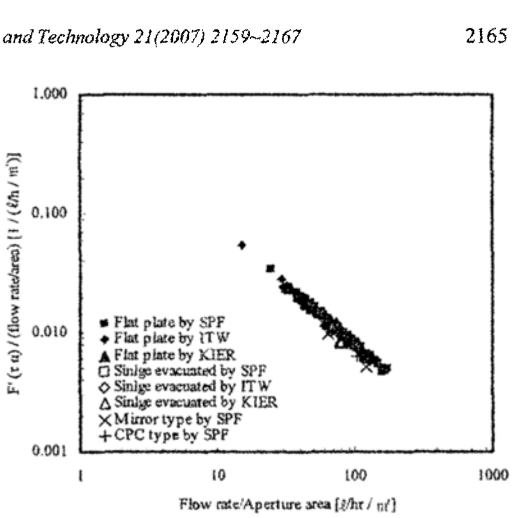


(a) $F'(\tau\alpha)$

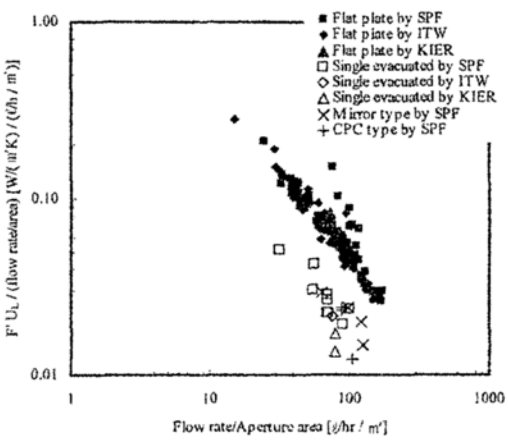


(b) $F'U_L$

Fig. 8. The characteristics of performance based on the unit volume flow rate.



(a) $F'(\tau\alpha)$



(b) $F'U_L$

Fig. 9. The characteristics of performance based on the unit characteristic scale.

$F'(\tau\ \alpha)$ and $F'U_L$. The type of solar collector was irrelevant to $F'(\tau\ \alpha)$ normalized by the aperture area, and the values obtained for the evacuated collectors were less than those for the flat-plate collectors. The values of $F'(\tau\ \alpha)$ and $F'U_L$ normalized by the aperture area decreased as the aperture area increased.

Fig. 9 shows $F'(\tau\ \alpha)$ and $F'U_L$ normalized to the proposed characteristic parameter of flow rate divided by aperture area. The physical significance of $F'(\tau\ \alpha)$ and $F'U_L$ is easily discernible. The type of solar collector was irrelevant to $F'(\tau\ \alpha)$, and the values of $F'U_L$ obtained for the evacuated collectors were less than those for the flat-plate collectors. In addition, $F'(\tau\ \alpha)$ and $F'U_L$ normalized to the proposed characteristic parameter decreased as the characteristic parameter increased.

To obtain a single parameter that describes the overall performance of a solar collector and includes all possible parameters, we defined our proposed modified heat loss coefficient as

$$U_L^* = \frac{\dfrac{F'\ U_L}{\eta_o}}{\dfrac{\dot{V}}{A_c}} = \frac{\dfrac{F'\ U_L}{F'\ (\tau\ \alpha)}}{\dfrac{\dot{V}}{A_c}} \quad . \tag{18}$$

Fig. 10 shows the performance of the solar collectors by using the modified heat loss coefficient. The behavior of the flat-plate and evacuated collectors was almost identical, while the modified heat loss coefficients of the evacuated collectors were less than those of the flat-plate collectors.

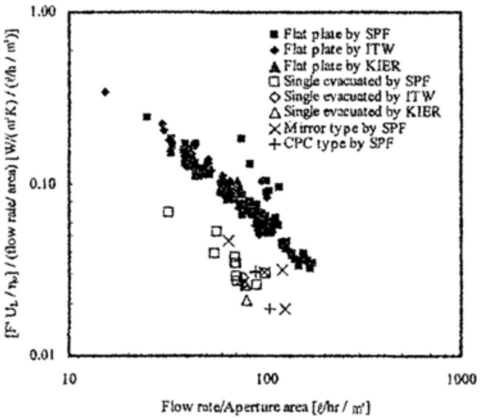
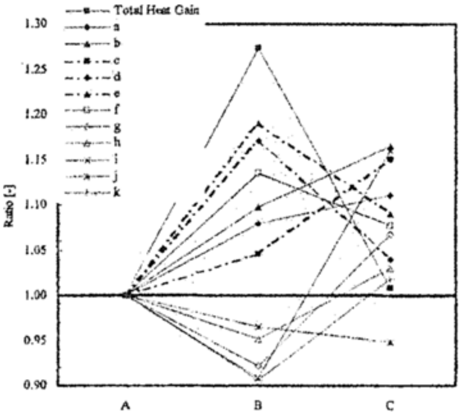
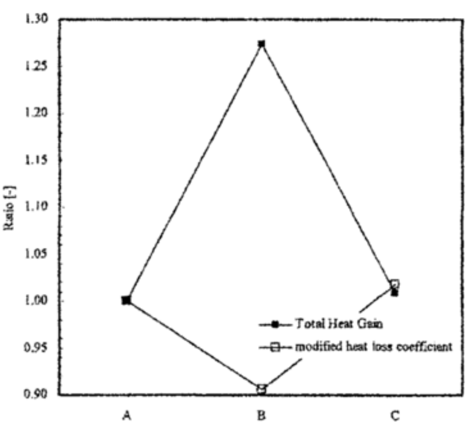


Fig. 10. The behavior of the modified heat loss coefficient.



(a) Comparison of the parameters considered with the total heat gain



(b) Total heat gain ratio and the modified heat loss coefficient ratio

Fig. 11. Demonstration of the validity of the modified heat loss coefficient.

Fig. 11 shows the validity of the proposed modified heat loss coefficient for the three flat-plate type solar collectors from manufacturers A, B, and C. Each collector had a different area and the performance tests were conducted using different flow rates. The following parameters were plotted: (a) $F'(\tau\alpha)$, $F'U_L$, (b) $F'U_L/Ac$, (c) $F'U_L/(\dot{V}/Ac)$, (d) $F'(\tau\alpha)/\dot{V}$, (e) $F'(\tau\alpha)/Ac$, (f) $F'(\tau\alpha)/(\dot{V}/Ac)$, (g) $F'U_L/F'(\tau\alpha)$, (h) $F'U_L/F'(\tau\alpha)/\dot{V}$, (i) $F'U_L/F'(\tau\alpha)/(1/Ac)$, (j) $F'U_L/F'(\tau\alpha)/(\dot{V}*Ac)$, and (k) $F'U_L/F'(\tau\alpha)/(\dot{V}/Ac)$. As Fig. 11 shows, $F'U_L/F'(\tau\alpha)/(\dot{V}/Ac)$ described the total heat gain behavior and considered all the parameters, including $F'U_L$, $F'(\tau\alpha)$, $\dot{V}$, and Ac. However, this approach must be tested in the field by using other solar collectors before it can be fully validated. Thus, additional studies are required.

4. Conclusions

We analyzed the methodology used to determine the efficiency of solar collectors and quantitatively showed the differences among the current institute testing standards. The type of solar collector was irrelevant to the values of $F'(\tau\alpha)$ normalized by either the aperture area or volume flow rate, and the value of $F'U_L$ normalized by either the aperture area or volume flow rate for an evacuated collector was less than that for a flat-plate collector. We propose a modified heat loss coefficient as a single parameter to describe the overall performance of a solar collector. The results of this study demonstrate that this coefficient better describes the thermal characteristics of various types of solar collectors than the existing methods.

Acknowledgments

We thank the ITW and SPF, whose test reports presented on their Web sites were used in this study.

Nomenclature

a	: Coefficient of collector performance	[W/m^2K]
a_1	: Coefficient of collector performance	[W/m^2K]
a_2	: Coefficient of collector performance	[W/m^2K^2]
Ac	: Collector surface area (aperture area)	[m^2]
C_p	: Liquid specific heat	[J/kg K]
F_R	: Heat-removal factor of the collector	
F'	: Collector efficiency factor	
G_T	: Global irradiance	[W/m^2]
Q_u	: Useful heat gain	[W]
k_1	: Coefficient of collector performance	[W/m^2K]

k_2 : Coefficient of collector performance [W/m^{2}K^2]
$\dot{m}$: Mass flow rate of the working fluid [kg/s]
T_a : Ambient temperature [K]
T_i : Inlet temperature of the working fluid [K]
T_m : Average temperature of the working fluid [K]
T_o : Outlet temperature of the working fluid [K]
T_m^* : Temperature difference per irradiance [K]
U_L : Overall heat loss coefficient [W/m^{2}K]
U_L^* : Modified heat loss coefficient [W/m^{2}K]
$\dot{V}$: Volume flow rate [L/h]
α : Absorptivity
η_o : Base efficiency of the collector
η : Collector efficiency
τ : Transmittance

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