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A SOLAR DOMESTIC HOT WATER SYSTEM SIMULATION STUDY IN SİVAS , TURKEY

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ABSTRACT

A simulation of the Domestic Hot Water (DHW) system, which will be installed in Sivas, is performed. A computer program written with the language of technical computing (MATLAB) is developed. First, the efficiency and the optimum design parameters of this system are computed. The results obtained are preserved in graphics and tables. An economical analysis of the system is also performed, and it is shown that the DHW system is necessary to reduce tomorrow's fuel bills.

Key words: Solar energy simulation, Solar collector, Domestic hot water

GÜNEŞ ENERJİLİ SICAK SU SİSTEMİ SİMÜLASYON ÇALIŞMASI: SİVAS ÖRNEĞİ

ÖZET

Sivas'ta konut içi kullanım amaçlı sıcak su temini için tasarlanan güneş enerjisi destekli bir sistemin simülasyonu yapılmıştır. Bu amaçla, MATLAB dilinde bir bilgisayar programı geliştirilmiştir. Sistem verimi ve optimum tasarım paremetreleri hesaplanmış ve elde edilen sonuçlar tablo ve grafiklerde verilmiştir. Tasarlanan sistemin ekonomik analizi de yapılmış ve bu sistemin sıcak su temini için kullanılan yakıt giderini azaltacağı sonucuna varılmıştır.

Anahtar Kelimeler: Güneş enerjisi simülasyonu, Güneş Toplayıcısı, Konut içi sıcak su

INTRODUCTION

The conventional energy resources (i.e fossil fuels, electrical energy) are widely used in supplying hot water but their amount is insufficient for the present world requirements. Therefore, the studies of alternative energy usability have continued about for 50 years and there have been significant developments in this field especially since the petroleum crises in the 1970 s. According to the results obtained it is found out that solar energy is very attractive because of having non-polluting qualities and being practically inexhaustible

The conventional energy systems are set up with the energy input determined by the user. In well-designed systems, the operational conditions depend on the desired output and their instantaneous efficiency is almost equal to daily average.

However, the solar energy systems are completely different, because their efficiency is affected by various operational and meteorological conditions. Besides, the energy input considerably changes depending on time. Solar energy may not supply the need at any time; therefore, energy storage is necessary.

According to the results of the earlier studies, it is not economical to design a system to meet all the need from solar energy because it is bulky and energy is collected when it is not required. For this reason, it is necessary to get a fraction of the energy need from the auxiliary energy resources.

In the present study, a simulation model of solar energy is developed in Sivas in order to supply domestic hot water. A simulation study is preferred because of the fact that it is less expensive and more time-saving than experimental study. The optimal system parameters and the efficiency of the system have been computed using a computer program.

Mathematical Model

The energy balance equation for a flat-plate collector is given by H.P.Gorg (1).

$$A_c I_T = \dot{Q}_u + \dot{Q}_{loss} + \frac{d\dot{Q}_i}{dt} \qquad (1)$$

where

$$\dot{Q}_{loss} = A_c U_L (T_p - T_a) \qquad (2)$$

Under steady state conditions, the last term in equation (1) can be neglected. Substituting equation (2) into equation (1), are can obtain

$$\dot{Q}_u = A_c\left[I_T(\tau\alpha)_e - U_L(T_p - T_a)\right] \quad (3)$$

where

$$(\tau\alpha)_e = 1.02(\tau\alpha) \quad (4)$$

and

$$(\tau\alpha) = (\tau\alpha)_n - b\left[1 - \frac{I_b}{I}\frac{R_b}{R}\left(2 - \frac{1}{\cos\theta}\right)\right] \quad (5)$$

where

$$\cos\theta = \cos\delta\cos\omega\cos(\phi-\beta) + \sin\delta\sin(\phi-\beta) \quad (6)$$

The overall heat-loss coefficient is written as

$$U_L = U_{top} + U_{back} + U_{edge} \quad (7)$$

where

$$U_{back} = \frac{K}{L} \quad (8)$$

The edge losses are small and usually negligible. An empirical equation for U_{top} is given by Agerwall and Larson [3]

$$U_{top} = \left\{\frac{N}{\frac{C}{T_p}\left[\frac{(T_p - T_a)}{(N+f)}\right]^{0.33}} + \frac{1}{h_w}\right\} + \frac{\sigma(T_p + T_a)(T_p^2 + T_a)^2}{\varepsilon_p + 0.05N(1-\varepsilon_p)^{-1} + \frac{2N+f-1}{\varepsilon_g} - N} \quad (9)$$

where

$$h_w = 5.7 + 3.8V \quad (10)$$

$$f = (1 - 0.04h_w + 0.0005h_w^2)(1 + 0.092N) \quad (11)$$

$$C = 250[1 - 0.044(\beta - 90)] \quad (12)$$

The maximum possible useful energy gain in a solar collector occurs when the whole collector is at the inlet fluid temperature; heat losses to the surroundings are then at a minimum. The collector heat removal factor times this maximum possible useful energy gain is equal to the actual useful energy gain, $\dot{Q}_u$

$$\dot{Q}_u = A_c F_R[S - U_L(T_i - T_a)] \quad (13)$$

where

$$F_R = \frac{\dot{m}C_p}{A_c U_L}\left\{1 - \exp\left[-\frac{A_c U_L F'}{\dot{m}C_p}\right]\right\} \quad (14)$$

and

$$S = (\tau\alpha)_e I_T \quad (15)$$

F' changes with the collector geometries. If the bond-conductance is neglected, the appropriate form of F' is as follows:

$$F' = \frac{1/U_L}{(D+W)\left[\frac{1/U_L}{D + W\eta_f} + \frac{1}{\pi D_i h_{f,i}}\right]} \quad (16)$$

The values of $h_{f,i}$ changes between 100 and 1500 W/m^2°C in terms of natural or forced circulation.

In equation (16)

$$\eta_f = \frac{\tanh(mW/2)}{(mW/2)} \quad (17)$$

where

$$m = \left(\frac{U_L}{k\delta}\right)^{1/2} \quad (18)$$

The instantaneous collector efficiency is written as

$$\eta = \frac{\dot{Q}_u}{A_c I_T} = \frac{q_u}{I_T} \quad (19)$$

where

$$q_u = \frac{\dot{Q}_u}{A_c} \quad (20)$$

If the equations (13) and (15) are introduced into equation (19) it yields

$$\eta = F_R\left[(\tau\alpha)_e - U_L\frac{(T_i - T_a)}{I_T}\right] \quad (21)$$

It is common to use the day-long collector efficiency in practice. It is determined for the mean day of the related month and calculated as

$$\eta_{day} = \frac{\sum q_u}{\sum I_T} \quad (22)$$

Available Solar Irradiation

While the thermal analysis of the collector is made, it is necessary to know the instantaneous global solar radiation data for long-term periods.

The ratio of I to the Q is given by Munroe(1980)

$$r_t = \frac{I}{Q} = \frac{\pi}{4t_o}\left[\cos\left(\frac{180}{2}\frac{\omega}{\omega_s}\right) + \frac{2}{\sqrt{\pi}}(1-\psi)^2\right] \quad (23)$$

where

$$\psi = \exp\left[-4\left(1-\frac{|\omega|}{\omega_s}\right)\right] \quad (24)$$

$$t_o = \frac{2}{15}\omega_s \quad (25)$$

$$\omega = 15(C-12) \quad (26)$$

and

$$\omega_s = \arccos(-\tan\delta\tan\phi) \quad (27)$$

The monthly average of daily diffuse radiation on the horizontal surface is

$$Q_d = Q - Q_b \quad (28)$$

The ratio of I_d to the Q_d is given by Liu and Jordan [5]

$$r_d = \frac{I_d}{Q_d} = \frac{\pi}{24}\left[\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\cos\omega_s}\right] \quad (29)$$

If equation (22) and (27) are introduced into equation (28) it yields

$$I_b = I - I_d = r_t Q - r_d Q_d \quad (30)$$

The instantaneous global solar radiation on fixed sloped surfaces is derived by Liu and

Jordan [5] . It is

$$R = \frac{I_b}{I}R_b + \frac{I_d}{I}\left(\frac{1+\cos\beta}{L}\right) + \rho\left(\frac{1-\cos\beta}{2}\right) = \frac{I_T}{I} \quad (31)$$

where

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\cos\omega + \sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} = \frac{I_{bT}}{I_b} \quad (32)$$

The ratio of monthly average of daily global solar radiation on sloped surfaces to the radiation on horizontal surface is

$$\overline{R} = \frac{Q_t}{Q} = \overline{R}_b\frac{Q_b}{Q} + \frac{Q_d}{Q}\left(\frac{1+\cos\beta}{2}\right) + \rho\left(\frac{1-\cos\beta}{2}\right) \quad (33)$$

where, for surfaces sloped toward the equator in the northern hemisphere, that is, for surfaces with $\gamma = 0$,

$$\overline{R}_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega_s' + (\pi/180)\omega_s'\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + (\pi/180)\omega_s\sin\phi\sin\delta} \quad (34)$$

where

$$\omega_s' = \min\begin{bmatrix}\cos^{-1}(-\tan\phi\tan\delta) \\ \cos^{-1}(-\tan(\phi-\beta)\tan\delta)\end{bmatrix} \quad (35)$$

where “min” means the smaller of the two items in the bracket.

Design of Domestic Hot Water (DHW) system

The monthly and annual water heating loads can be calculated respectively:

$$L_{w,i} = C_p DD_i \quad (36)$$

where

$$DD_i = M(T_w - T_m) \quad (37)$$

and

$$L_w = C_p DD \quad (38)$$

where

$$DD = \sum_{i=1}^{12} C_p DDi \quad (39)$$

The monthly fractions of loads met by solar energy are

$$f_i = \frac{Q_{u,i}}{L_{w,i}} \quad (40)$$

where

$$Q_{u,i} = \sum_{i=1}^{12} Q_u \eta_{day} n_i \quad (41)$$

The annual useful energy collected by flat-plate collector can be written

$$Q_{u,y} = \sum_{i=1}^{12} Q_{u,i} \quad (42)$$

The collector area and storage unit volume are

$$A_c = \frac{Q_{u,y}F}{L_w} \quad (43)$$

$$V_s = 70A_c \quad (44)$$

Procedure

The system in this simulation is shown in Figure 1. It provides hot water for a four people family. The hot water demand is 200 Liters/day. The collector in this system is the one covered and nonselective. The bond-conductance is neglected in calculating collector efficiency factor. The mass flow rate of antifreeze solution is 0.015 kg /s. m^2 . The collector slope is the same as longitude of Sivas and its azimuth angle is zero. The effect of

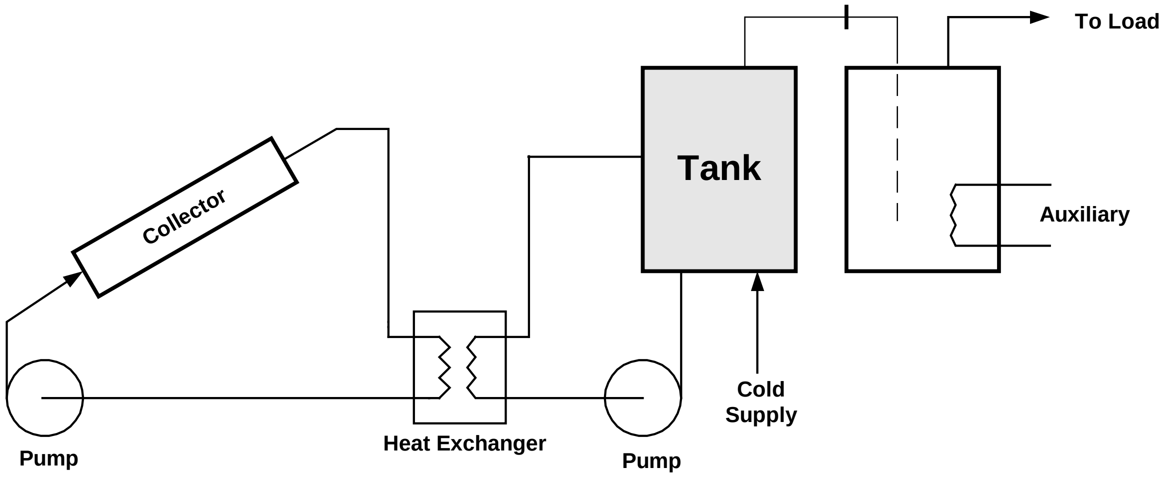

Fig. 1. Schematic of the system with the antifreeze loop and external heat exchanger

the heat exchanger factor on the collector efficiency is considered in the calculation. The collector heat exchanger inside the tank is assumed to have an effectiveness of 0.7. Ground reflectance is assumed to be 0.2 at all times. The values of $(\tau\alpha)_n$ and b are taken 0.87 and 0.07 respectively.

The changes of U_L and $(\tau\alpha)_e$ with the wind speed , incidence angle and plate temperature are taken into account. The inlet fluid temperature is constant.

study are taken from Taşdemiroğlu and Ecevit (1985).

Results and Discussion

The simulation of the domestic hot water system is carried out and the results obtained are preserved in the graphs and tables.

Figure 2 shows the monthly fraction of loads carried by solar energy for a four people family. If the annual solar fraction is 50% , the collector area and storage volume are 3.082 m^2 and 0.216 m^3

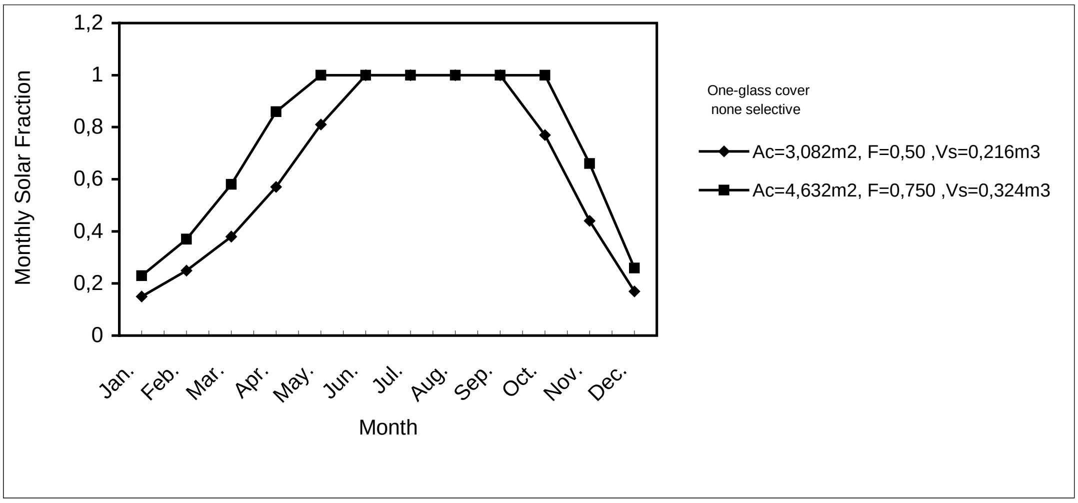

Fig. 2. The change of the monthly solar fraction with the months

A computer program based on formulations given above is used. It is written with the language of technical computing (MATLAB) . The degree – day method is used to determine the annual hot water demand. Instantaneous efficiency of the collector is computed with the hour by hour analysis. The meteorological data used in this

respectively. In the case of 75 % their values are 4.632 m^2 and 0.324 m^3. If the annual solar fraction is 50 % , all the need can be met by solar energy from June to October but in winter months the monthly solar fraction is less than 50 %. If it is 75 % , all the need can be met by solar energy from

May to November but the monthly solar fraction is less than 75 % in the other months.

The change of the monthly system efficiency with the months is shown in Figure 3. The mean day of the related month is taken as a basis in the calculations. The inlet fluid temperature is kept constant during the year and the calculation is done for 1 m^2 collector area. It is seen that the smallest value of the efficiency is 0.267 , which occurs in January and that the biggest value is 0.616 , which occurs in August.

Figure 4 shows the change of the collected energy with the months. As the collected energy meets all the need from June to October, the auxiliary energy is needed in the other months. In this case, the annual solar fraction is 50%. When the annual solar fraction is 75% , the collected energy meets all the need from April to November but the auxiliary energy is needed in the other months.

The annual energy need for a four people family in Sivas is calculated as 14.46 GJ from equation (37). Fossil fuels and electricity are widely used in Sivas to meet this energy need . Their some properties are shown in Table 1.

The annual fuel need and fuel cost can be calculated from the following equations.

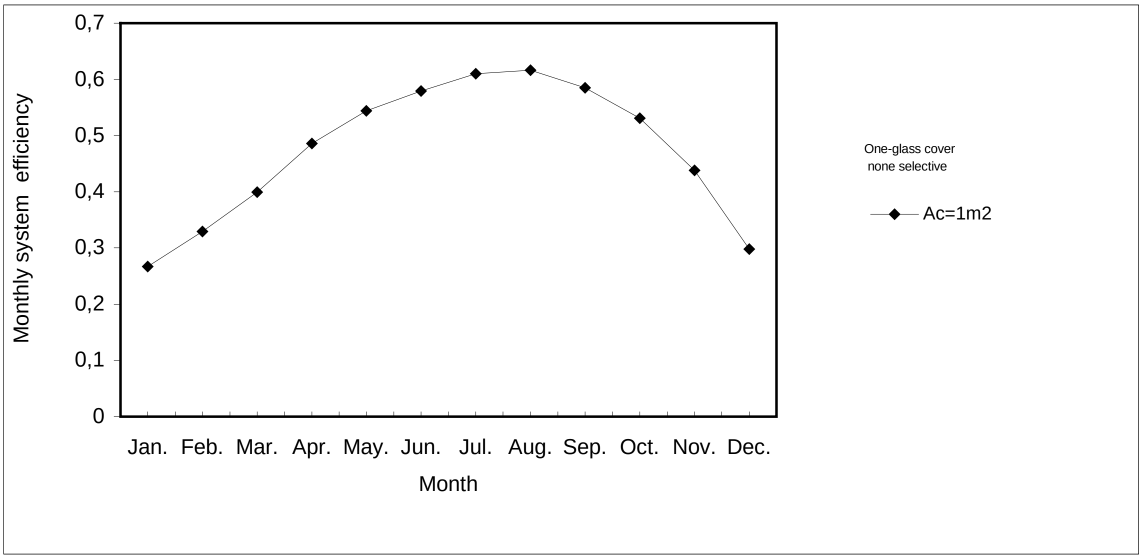

Fig 3.The change of the monthly system efficiency with the months

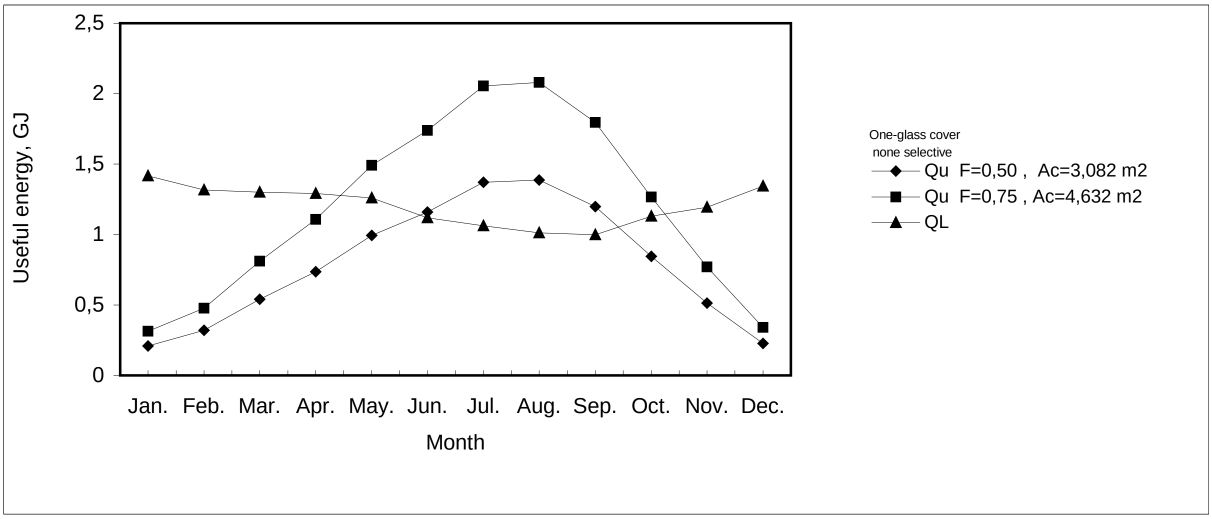

Fig 4.The change of the useful energy with the months

Table 1. Economical analysis of solar domestic hot water system

Fuel type	Conventional Energy Resources		Solar Energy			
	Fuel amount	Fuel cost (June 2001) (10^6 TL/year)	Fuel amount f = 0.50	f =0.75	Fuel cost(June 2001) (10^6 TL/year) f = 0.50	f = 0.75
Natural gas	424 m^3 / year	133.8	212 m3 / year	106 m^3 / year	66.9	33.45
LPG	312 kg / year	407.7	156 kg / year	78kg / year	203.85	101.9
Coal	636 kg / year	121.9	318 kg / year	159 kg / year	60.95	30.50
Fuel-Oil	380 kg / year	212.2	190 kg / year	95 kg / year	106.1	53.05
Electiricity	4064 kWh / year	420.8	2032 kWh / year	1016 kWh / year	210.4	105.2

Fuel need = Annual energy need / Calorific value of the fuel

Fuel cost = (Fuel need / Combustion efficiency). Fuel price

The results obtained are summarized in Table 1.

CONCLUSION

The energy need for domestic hot water supply is 12 per cent of the whole energy. Fossil fuels and electricity are commonly used to supply hot water. Recently, US, Australia and Japan, which have high solar energy potential, supply the major fraction of the energy for domestic hot water from solar energy. In addition to them, solar energy usability is supported by many countries in the World.

Although Sivas has a high solar energy potential , the rate of its usability is very small. Whereas, 50-75 % of the annual energy need can be provided by the flat plate collectors , placed on the roof , to the south. Thus expenditures will decrease and considerably economical gains will be obtained.

As a result, the studies of solar energy usability should be supported by local government because of the increasing energy need and air pollution.

Nomenclature

A_c Collector area (m^2)

C_p Specific heat of the antifreeze solution (J/kg-K)

C Solar time

D Tube diameter (mm)

D_i Inside tube diameter (mm)

DD_i The number of degree-days in the month

f_i The monthly solar fraction(%)

F_R The collector heat removal factor

F' The collector efficiency factor.

F The annual solar fraction(%)

h_w Wind heat transfer coefficient(W/m^2 °C)

$h_{f,I}$ Heat transfer coefficient between the fluid and tube wall (W/m^2 °C)

I_d The instantaneous beam radiation on the horizontal surface (W/m^2)

I The instantaneous global solar radiation on the horizontal surface (W/m^2)

I_T Solar irradiation on a collector surface (W/m^2)

k Plate thermal conductivity (W/m °C)

K The insulation thermal conductivity (W/m °C)

L The insulation thickness (mm)

L_{wi} The monthly water heating loads (GJ/month)

L_w The annual water heating loads (GJ/year)

$\dot{m}$ Mass flow rate of the antifreeze solution (kg/sm^2)

n_i Number of days in the month.

N Number of glass covers

$Q_{u,I}$ The monthly useful energy collected by flat-plate collector(GJ/month)

Q_t Monthly average of daily global solar radiation on tilted surface (MJ/m^2 day)

Q_d Monthly average of daily diffuse radiation on the horizontal surface(MJ/m^2 day)

Q_b Monthly average of daily beam radiation on the horizontal surface(MJ/m^2 day)

$Q_{u,y}$ The annual useful energy collected by flat-plate collector(GJ/year)

Q Monthly average daily global solar radiation on the horizontal surface (MJ/m^{2}day)

$\dot{Q}_U$ Rate of heat transfer from the collector absorber plate to the working fluid (W)

Rate of heat transfer from the collector to the surroundings (W)

$\dot{Q}_i$ Rate of internal energy storage in the collector (W)

W Distance between the tubes (mm)

U_L The overall heat-loss coefficient (W/m^2.K)

t_o The number of daylight hours

T_w Set temperature for delivery of hot water(°C)

T_m Mains (supply) water temperature(°C)

T_i Inlet fluid temperature (°C)

T_p Average plate temperature (°C or K)

T_a Average ambient temperature (°C or K)

$(\tau\alpha)_e$ Effective transmittance-absorbance product.

$(\tau\alpha)$ Transmittance-absorbance product.

β Collector tilt (degrees)

δ Declination, plate thickness (mm)

ε_g Emittance of glass

ε_p Emittance of plate

ϕ Latitude (degrees)

γ Surface azimuth angle (degrees).

η_f Fin efficiency

θ Angle of Incidence

ρ Diffuse ground reflectance

σ Stefan-Boltzman constant=5.67x10^{-8}

ω Hour angle(degrees)

ω_s Sunset hour angle

ω_s' The sunset hour angle for the tilted surface for the mean day of the month

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