MODELING AND DESIGN OF SOLAR ENERGY SYSTEMS INCLUDING SOLAR ECONOMICS

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Contents

Summary

The design of a solar energy system is a complex problem. As such it includes both predictable and unpredictable parameters. The former are related to performance characteristics of collectors and other components and the latter mainly concern weather data such as solar radiation, ambient temperature, wind speed and direction, and other

less important environmental parameters. In this chapter, a simple design method and a simple modeling technique are presented as well as an overview of TRNSYS which is the simulation program suitable for modeling active solar heating systems. The design method presented is the *f*-chart. This is based on the correlation of the results of a large number of TRNSYS simulations in terms of easily calculated dimensionless variables. The *f*-chart can be used to model active liquid and air systems and active systems used to provide only hot water. These are explained in this chapter together with a modification to use the method for estimating the performance of thermosiphon solar water heating systems, which constitute the great majority of solar water heating systems. This is followed by simple models of solar energy systems suitable for analysis of the systems on hourly basis. In recent years, because of the increase of computational speed of personal computers, annual simulations have replaced design methods. Design methods however, are much faster; therefore they are still useful in early design studies. For more detailed results modeling and simulation is used. The software programs described briefly in this chapter include the *F*-chart and TRNSYS. Finally, the way to perform economic analysis of solar energy systems is presented and in particular the life cycle analysis. It is also indicated how to optimize a solar energy system using the economic analysis.

1. *F*-Chart Method

The *f*-chart is a simple method used for estimating the annual thermal performance of active heating systems using liquid or air as a working fluid and where the minimum temperature of energy delivery is near 20°C. The configurations of the systems which can be evaluated by the *f*-chart method are commonly found in residential applications. The *f*-chart method is used to estimate easily the fraction of the total heating load that can be supplied by the solar energy system called the solar contribution. If the energy required for a fuel-only system or the energy required to cover the load is denoted by Q_{L}, the auxiliary energy for a solar energy system is denoted by Q_{AUX} and the solar energy delivered is Q_{S}, then for a solar energy system:

$$Q_{\mathrm{L}} = Q_{\mathrm{AUX}} + Q_{\mathrm{S}} \tag{1}$$

For a month i, the fractional reduction of energy when a solar energy system is used, called the solar fraction or solar contribution, f, is given by the ratio:

$$f = \frac{Q_{\mathrm{L},i} - Q_{\mathrm{AUX},i}}{Q_{\mathrm{L},i}} \tag{2a}$$

which by the help of Eq. (1) is equal to:

$$f = \frac{Q_{\mathrm{S},i}}{Q_{\mathrm{L},i}} \tag{2b}$$

The *f*-chart method was originally developed by Klein and Beckman. The method is in fact a correlation of the output of hundreds of thermal performance simulations of solar heating systems carried out with TRNSYS (see section 2.3) performed in such a way so the simulation conditions were varied over a specific range of parameters corresponding to practical system designs. These ranges are shown in Table 1. In the *f*-chart method, the primary design variable is the collector area. Secondary variables can be the storage capacity, collector type, thermal load, collector heat exchanger size and fluid flow rate. The resulting correlations give the fraction of the monthly load supplied by solar energy, *f*, as a function of two dimensionless parameters, namely:

- The ratio of collector losses to heating load, and
- The ratio of absorbed solar radiation to heating load.

Heating load includes both space heating and hot water loads. The *f*-chart method has been developed for three standard system configurations; liquid and air systems for space and hot water heating and systems for service hot water only. All these systems are active which means that they use a pump or fan for the fluid circulation and the method considers that the storage tank of the solar energy system is fully mixed. Later on the method was modified to be used for thermosiphon systems where the storage tank is stratified and the flow in the collector occurs by natural means.

Parameter	**Range**
Transmittance-absorptance product at normal incidence - $(\tau\alpha)_n$	0.6-0.9
Product of heat removal factor with heat exchanger and collector area - $F'_R A_c$	5-120 m^2
Collector heat loss coefficient - U_L	2.1-8.3 W/m^2-°C
Collector slope from horizontal - β	30-90°
Overall energy loss coefficient and area product for a building used in a degree day space heating load - $(UA)_h$	83.3-666.6 W/°C

Table 1. Range of design variables used in developing *f*-charts for liquid and air systems

The solar energy delivered Q_S, can be obtained by integrating over a time period Δt the useful energy collected by a solar collector system. Thus using the definition of the solar fraction, f, from Eq. (2b), we get:

$$f = \frac{Q_S}{Q_L} = \frac{1}{Q_L}\int_{\Delta t} Q_u^+ dt \tag{3}$$

where Q_L = total heating load during the integration period (MJ)

The useful energy collected by the solar energy system Q_u, is obtained by the following relation:

$$Q_u = A_c F_R \left[G_t(\tau\alpha) - U_L \left(T_i - T_a \right) \right], \tag{4}$$

where F_R is the heat removal factor, which represents the ratio of the actual useful energy gain that would result if the collector-absorbing surface had been at the local fluid temperature, given by:

$$F_R = \frac{\dot{m}c_p}{A_c U_L}\left(1 - \exp\left[-\frac{U_L F' A_c}{\dot{m}c_p}\right]\right). \tag{5}$$

In Eq. (4) by replacing F_R by F'_R, to account for the presence of a heat exchanger in the solar collection network as is explained subsequently, and G_t, the total incident radiation (beam and diffuse), by H_t, the total insolation over a day, Eq. (3) can be written as:

$$f = \frac{A_c F_R}{Q_L}\int_{\Delta t}\left[H_t(\tau\alpha) - U_L\left(T_s - T_a\right)\right]dt\,. \tag{6}$$

The last term of Eq. (6) can be multiplied and divided by the term $\left(T_{ref} - T_a\right)$, where T_{ref} is a reference temperature chosen to be 100°C, so Eq. (6) can be written as:

$$f = \frac{A_c F'_R}{Q_L}\int_{\Delta t}\left[H_t(\tau\alpha) - U_L\left(T_{ref} - T_a\right)\frac{\left(T_s - T_a\right)}{\left(T_{ref} - T_a\right)}\right]dt\,. \tag{7}$$

In any solar energy system the resulting storage tank temperature T_s, is a complicated function of H_t, Q_L and T_a, therefore Eq. (7) cannot be explicitly integrated and evaluated. It suggests however, that an empirical correlation can be found, on a monthly basis, between the solar fraction, f, and the two dimensionless groups mentioned earlier as follows:

$$X = \frac{A_c F'_R U_L}{Q_L}\int_{\Delta t}\left(T_{ref} - \bar{T}_a\right)dt = \frac{A_c F'_R U_L}{Q_L}\left(T_{ref} - \bar{T}_a\right)\Delta t \tag{8}$$

$$Y = \frac{A_c F'_R}{Q_L}\int_{\Delta t} H_t\left(\tau\alpha\right)dt = \frac{A_c F'_R}{Q_L}(\overline{\tau\alpha})\bar{H}_t N\,, \tag{9}$$

where Q_L = monthly heating load or demand (MJ)

N = number of days in a month

$\bar{T}_a$ = monthly average ambient temperature (°C)

$\bar{H}_t$ = monthly average daily total radiation on the tilted collector surface (MJ/m^2)

$(\overline{\tau\alpha})$ = monthly average value of $(\tau\alpha)$, which is equal to the monthly average value of absorbed over incident solar radiation, given by:

$$(\overline{\tau\alpha}) = \frac{\bar{S}}{\bar{H}_{\mathrm{t}}} \tag{10}$$

The dimensionless parameters X and Y, given by Eqs. (8) and (9) are usually rearranged to use the factors $F_{\mathrm{R}}U_{\mathrm{L}}$ and $F_{\mathrm{R}}\left(\tau\alpha\right)_{\mathrm{n}}$ which are readily available from standard collector tests and therefore they become:

$$X = F_{\mathrm{R}}U_{\mathrm{L}}\,\frac{F'_{\mathrm{R}}}{F_{\mathrm{R}}}(T_{\mathrm{ref}} - \bar{T}_{\mathrm{a}})\Delta t\,\frac{A_{\mathrm{c}}}{Q_{\mathrm{L}}} \tag{11}$$

$$Y = F_{\mathrm{R}}(\tau\alpha)_{\mathrm{n}}\,\frac{F'_{\mathrm{R}}}{F_{\mathrm{R}}}\left[\frac{(\overline{\tau\alpha})}{(\tau\alpha)_{\mathrm{n}}}\right]\overline{H}_{\mathrm{t}}N\,\frac{A_{\mathrm{c}}}{Q_{\mathrm{L}}} \tag{12}$$

The physical significance of the two dimensionless parameters X and Y is that the parameter X represents the ratio of the reference collector total energy loss to total heating load or demand (Q_{L}) during the period Δt, whereas the parameter Y represents the ratio of the total absorbed solar energy to the total heating load or demand (Q_{L}) during the same period.

The ratio $F'_{\mathrm{R}}/F_{\mathrm{R}}$ in Eqs. (11) and (12) is used to correct the collector performance to account for the presence of a heat exchanger which causes the collector side of the system to operate at higher temperature than a similar system without a heat exchanger and is given by:

$$\frac{F'_{\mathrm{R}}}{F_{\mathrm{R}}} = \left[1 + \frac{A_{\mathrm{c}}F_{\mathrm{R}}U_{\mathrm{L}}}{\left(\dot{m}c_{\mathrm{p}}\right)_{\mathrm{c}}}\left(\frac{\left(\dot{m}c_{\mathrm{p}}\right)_{\mathrm{c}}}{\varepsilon\left(\dot{m}c_{\mathrm{p}}\right)_{\min}} - 1\right)\right]^{-1} \tag{13}$$

where $\left(\dot{m}c_{\mathrm{p}}\right)_{\min}$ = smaller of the fluid capacitance rates of the collector and tank sides of the heat exchanger (W/°C)

ε = heat exchanger effectiveness (-).

For a given collector orientation, the value of the factor $(\overline{\tau\alpha})/\left(\tau\alpha\right)_{\mathrm{n}}$ in Eq. (12) varies slightly from month to month. For collectors tilted and facing the equator with a slope equal to latitude plus 15°, Klein found that the factor is equal to 0.96 for one-cover collector and 0.94 for two-covers collectors for the whole heating season (winter months). Using Eq. (10) for the relation of $(\overline{\tau\alpha})$:

$$\frac{\left(\overline{\tau\alpha}\right)}{\left(\tau\alpha\right)_{\mathrm{n}}} = \frac{\bar{S}}{\bar{H}_{\mathrm{t}}\left(\tau\alpha\right)_{\mathrm{n}}}. \tag{14}$$

If the isotropic model is used, $\bar{S}$ is given by:

$$\bar{S} = \bar{H}_{\mathrm{B}}\bar{R}_{\mathrm{B}}(\overline{\tau\alpha})_{\mathrm{B}} + \bar{H}_{\mathrm{D}}(\overline{\tau\alpha})_{\mathrm{D}}\left(\frac{1+\cos(\beta)}{2}\right) + \bar{H}\rho_{\mathrm{G}}(\overline{\tau\alpha})_{\mathrm{G}}\left(\frac{1-\cos(\beta)}{2}\right). \tag{15}$$

Therefore, by substituting in Eq. (14) gives:

$$\frac{\left(\overline{\tau\alpha}\right)}{\left(\tau\alpha\right)_{\mathrm{n}}} = \frac{\bar{H}_{\mathrm{B}}\bar{R}_{\mathrm{B}}}{\bar{H}_{\mathrm{t}}}\frac{\left(\overline{\tau\alpha}\right)_{\mathrm{B}}}{\left(\tau\alpha\right)_{\mathrm{n}}} + \frac{\bar{H}_{\mathrm{D}}}{\bar{H}_{\mathrm{t}}}\frac{\left(\overline{\tau\alpha}\right)_{\mathrm{D}}}{\left(\tau\alpha\right)_{\mathrm{n}}}\left(\frac{1+\cos(\beta)}{2}\right) + \frac{\bar{H}\rho_{\mathrm{G}}}{\bar{H}_{\mathrm{t}}}\frac{\left(\overline{\tau\alpha}\right)_{\mathrm{G}}}{\left(\tau\alpha\right)_{\mathrm{n}}}\left(\frac{1-\cos(\beta)}{2}\right). \tag{16}$$

The term $\bar{R}_{\mathrm{B}}$ is the ratio of the monthly average beam radiation on a tilted surface to that on a horizontal surface, called the monthly mean beam radiation tilt factor. This is a complicated function of the atmospheric transmittance, but it can be estimated by the ratio of extraterrestrial radiation on the tilted surface to that on a horizontal surface for the month. For surfaces facing directly towards the equator this is given by:

$$R'_{\mathrm{B}} = \frac{\cos(L-\beta)\cos(\delta)\sin(h'_{\mathrm{ss}}) + (\pi/180)h'_{\mathrm{ss}}\sin(L-\beta)\sin(\delta)}{\cos(L)\cos(\delta)\sin(h_{\mathrm{ss}}) + (\pi/180)h_{\mathrm{ss}}\sin(L)\sin(\delta)} \tag{17a}$$

where h'_{ss} is sunset hour angle on the tilted surface (degrees) given by:

$$h'_{\mathrm{ss}} = \min\{h_{\mathrm{ss}}, \cos^{-1}\left[-\tan\left(L-\beta\right)\tan\left(\delta\right)\right]\}. \tag{17b}$$

For the southern hemisphere the term $\left(L-\beta\right)$ of Eqs. (17a) and (17b) need to change to $\left(L+\beta\right)$.

In Eq. (16) the $(\overline{\tau\alpha})/\left(\tau\alpha\right)_{\mathrm{n}}$ ratios can also be obtained from graphs given in the original paper of Klein or from the following curve fit equations:

For single cover:

$$\frac{(\overline{\tau\alpha})}{(\tau\alpha)_{\mathrm{n}}} = -8.7x10^{-8}\theta^4 + 1.03x10^{-5}\theta^3 - 0.0004762\theta^2 + 0.00851\theta + 0.94967. \tag{18a}$$

For 2 covers:

$$\frac{(\overline{\tau\alpha})}{(\tau\alpha)_{\mathrm{n}}} = -5.05x10^{-8}\theta^4 + 3.578x10^{-6}\theta^3 - 8.777x10^{-5}\theta^2 - 1.836x10^{-6}\theta + 1.0042, \tag{18b}$$

where θ is the incidence angle in degrees.

Equations (18a) and (18b) are for one and two sheet of collector glass covers respectively with refractive index equal to 1.526. The various components of $(\overline{\tau\alpha})/(\tau\alpha)_\text{n}$ in Eq. (16), i.e., the beam, diffuse and ground reflected components are obtained from Eqs. (18a) and (18b) by using the appropriate mean incidence angle. For the beam component the effective angle of incidence $\overline{\theta}_\text{b}$, also called mean incidence angle for beam radiation, can be obtained from the original figures of Klein and for surfaces facing directly towards the equator it can be approximated as the incidence angle at 2.5 hours from solar noon on the average day of the month shown in Table 2 together with other useful parameters like the day number, the declination at that day, δ, and β_m, the monthly optimal collector tilt angle.

Month	Day	Day No.	δ (deg.)	β_m (deg.)
January	17	17	-20.92	L+29
February	16	47	-12.95	L+18
March	16	75	-2.42	L+3
April	15	105	9.41	L-10
May	15	135	18.79	L-22
June	11	162	23.09	L-25
July	17	198	21.18	L-24
August	16	228	13.45	L-10
September	15	258	2.22	L-2
October	15	288	-9.60	L+10
November	14	318	-18.91	L+23
December	10	344	-23.05	L+30

Table 2. Recommended average day for each month, declination for that day and monthly optimal tilt angle

For the diffuse and ground reflected components of radiation at the effective incidence angles at β, the mean incidence angles can be obtained from:

$$\theta_\text{e,D} = 59.68 - 0.1388\beta + 0.001497\beta^2 \tag{19}$$

$$\theta_\text{e,G} = 90 - 0.5788\beta + 0.002693\beta^2 \tag{20}$$

Generally, *f*-chart is used to estimate the monthly solar fraction, f_i. The energy contribution for the month, i, is the product of f_i and monthly load (heating and hot water), $Q_{\text{L},i}$, i.e., $f_i Q_{\text{L},i}$ *i*. The fraction on an annual basis of the annual load supplied by the solar energy system, F, is the sum of the monthly energy contributions divided by the annual load, given by:

$$F = \frac{\sum f_i Q_{L,i}}{\sum Q_{L,i}} \tag{21}$$

It should be noted that although the method primarily depends on values obtained from charts, hence its name, here only the main *f*-charts and equations are given. Other complimentary charts can be found from the original references or from books. However, the interested reader can easily create the appropriate charts using any spreadsheet program or the spreadsheet program can be used to obtain the required values easily and more accurately without having to perform a large number of hand calculations.

It should be pointed out again that the method can be used to simulate standard solar water and air systems configurations and solar energy systems used only for hot water production. These are examined separately in the following sections.

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Bibliography

Beckman W.A., Klein S.A., Duffie J.A., *Solar Heating Design by the f-chart Method*, Wiley-Interscience, New York, 1977. [A book presenting the f-chart method in detail, giving step-by-step procedures on how to design solar energy systems with this method].

Brandemuehl M.J., Beckman W.A., Economic evaluation and optimization of solar heating systems, *Solar Energy*, Vol. 23, No. 1, p. 1-10, 1979. [This presents a method of economic evaluation of solar heating systems using uncertainty analysis].

Copsey A.B., Modification of the *f*-chart method for solar domestic hot water systems with stratified storage, MS Thesis, University of Wisconsin, 1984. [This thesis presents the modifications required to the *f*-chart method in order to be able to be used for the design of small solar hot water heating systems with stratified storage tanks].

Duffie J.A., Beckman W.A., *Solar Engineering of Thermal Processes*, Third Edition, John Wiley & Sons, New York, 2006. [A comprehensive book giving design details and procedures for almost all solar energy systems and processes].

Evans D.L., Rule T.T., Wood B.D., A new look at long term collector performance and utilisability, *Solar Energy*, Vol. 28, pp. 13-23, 1982. [In this the solar collector performance is viewed with respect to its utilizability, which is a method used to design solar heating systems].

Fanney A.H., Klein S.A., Performance of solar domestic hot water systems at the National Bureau of Standards, *Journal of Solar Energy Engineering*, Vol. 105, pp. 311-321, 1983. [This presents the performance of five liquid based solar hot water systems monitored at the National Bureau of Standards].

Kalogirou S.A., Economic analysis of solar energy systems using spreadsheets, *Proceedings of the World Renewable Energy Congress IV*, Denver, Colorado, USA, Vol. 2, pp. 1303-1307, 1996. [This explains the steps required to perform and economic analysis of solar energy systems using spreadsheets].

Kalogirou S.A., The potential of solar industrial process heat applications, *Applied Energy*, Vol. 76, No. 4, pp. 337-361, 2003. [This examines a number of solar thermal systems as applied to industrial process heat applications].

Kalogirou S.A., Environmental benefits of domestic solar energy systems, *Energy Conversion and Management*, Vol. 45, No. 18-19, pp. 3075-3092, 2004. [This examines the environmental benefits of domestic solar energy systems in terms of the emissions to the environment and the embodied energy required to construct a solar flat-plate collector].

Kalogirou S.A., *Solar Energy Engineering: Processes and Systems*. Academic Press, New York, 2009. [A comprehensive book giving design details and procedures of almost all solar energy collectors, systems and processes including photovoltaics].

Klein S.A., Calculation of monthly-average transmittance-absorptance product, *Solar Energy*, Vol. 23, No. 6, pp. 547-551, 1979. [This presents the method suggested by Klein for the calculation of monthly-average transmittance-absorptance product].

Klein S.A., Beckman W.A., Duffie J.A., A design procedure for solar heating systems, *Solar Energy*, Vol. 18, No. 2, pp. 113-127, 1976. [This presents the f-chart method for the design of solar water heating systems].

Klein S.A., Beckman W.A., Duffie J.A., A design procedure for solar air heating systems, *Solar Energy*, Vol. 19, No. 6, pp. 509-512, 1977. [This presents the f-chart method for the design of solar air heating systems].

Klein S.A., Beckman W.A., *F-Chart Users Manual*, University of Wisconsin, 2005. [This is the manual of the F-Chart program which gives details not only on how to operate the program but also for the f-chart method itself].

Liu B.Y.H., Jordan R.C., *Availability of Solar Energy for Flat Plate Solar Heat Collectors*, In Liu B.Y.H., Jordan R.C. (Eds.), ASHRAE, Atlanta, GA, 1977. [This book introduces the solar energy availability as a design method for flat-plate solar collectors].

Malkin M.P., Klein S.A., Duffie J.A., Copsey A.B., A design method for thermosiphon solar domestic hot water systems, *Transactions of ASME*, Vol. 109, pp. 150-155, 1987. [This gives details of the modifications required to the f-chart in order to be able to be used for the design of thermosiphon domestic solar water heating systems].

Malkin M.P., *Design of thermosiphon solar domestic hot water systems*, MS Thesis, University of Wisconsin, 1985. [This thesis presents the modifications required to the f-chart in order to be able to be used for the design of small thermosiphon solar water heating systems which due to low flow rate have stratified storage tanks].

Mitchell J.C., Theilacker J.C., Klein S.A., Calculation of monthly average collector operating time and parasitic energy requirements, *Solar Energy*, Vol. 26, pp. 555-558, 1981. [This gives details of the method for the calculation of the monthly average collector operating time and parasitic energy requirements, which are useful in solar energy system design].

Phillips W.F., Dave R.N., Effects of stratification on the performance of liquid-based solar heating systems, *Solar Energy*, Vol. 29, pp. 111-120, 1982. [This examines the effects of stratification on the performance of liquid-based solar heating systems and shows its importance for the effective operation of the systems].

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