SCF II Project

Procedures for the certification of performance of large custom-made solar thermal systems, with particular emphasis on the modelling tools (SK-LCMSTS)

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Modelling tools for the prediction of performance of large custom-made solar thermal systems

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1. Introduction

Dealing with the issues of quality assurance as well as of the market and investment requirements and in view of the availability of the EN 12977 series standard for custom-built systems, the integration of the Solar Keymark Scheme Rules for "*large custom-built systems*", by investigating the possibility of the accurate thermal performance prediction becomes a necessary prerequisite for the further development in this field of applications.

The aim of this report regards the investigation of the modelling methods offered in the relevant scientific literature, resulting in efficient tools for the thermal performance prediction and/or verification of *large custom-built solar thermal systems* (as defined in the EN 12977 Standard series).

2. Definitions and classification of solar heating systems

Solar heating systems, as described in the EN 12976 and EN 12977 series Standards, are distinguished in two categories:

Factory-made solar heating systems as batch products with one trade name, sold as complete and ready to install kits, with fixed configurations and *Custom-built solar heating systems* either uniquely built or assembled by choosing from an assortment of components.

Custom-built solar heating systems are subdivided into two categories. *Small custom-built systems* offered by a company are described in a so-called assortment file, in which all components and possible system configurations, marketed by the company, are specified. In general, the collector area is greater than 1 m^2 and less than 30 m^3 and the store volume is less than 3 m^3. *Large custom-built systems*, are defined those uniquely designed by combining various components for a specific situation and which could be used either for hot water preparation and/or space heating/cooling. In general, the collector area of those systems is greater than 30 m^2 and the store volume is greater than 3 m^3.

Large custom built systems are classified as *Class A* (stores and collector arrays are located in one building), *Class B* (central heating/cooling plant and one or more collector arrays), *Class C* (one or more large collector arrays in which the heat/cool is transferred to a seasonal store or directly into a heat/cool distribution network) or D (of any other type).

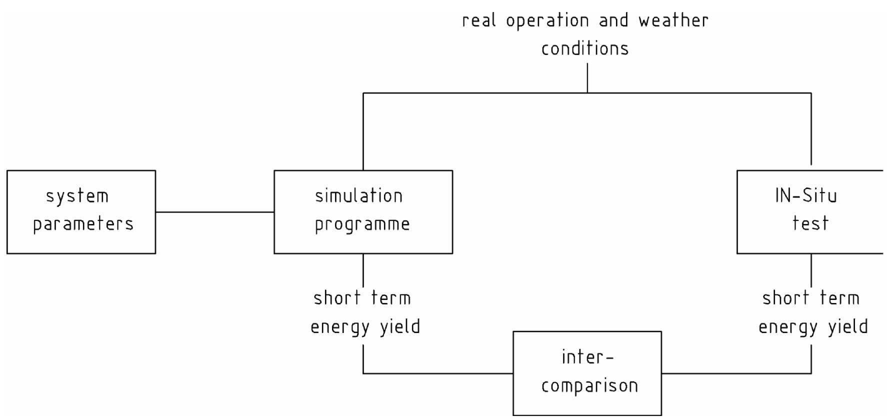
3. Performance Prediction Requirements

There are no requirements for the performance prediction for the *large custom-built systems*, as stated in the EN 12977-1 Standard. However, if monitoring of the system is considered, it is recommended to use the methods described in EN 12977-2. As *large custom-built systems* are by definition unique systems, only general procedures on how to check and supervise them may be given. In the annexes C and D of the EN 12977-2 Standard several possible levels of analysis are included.

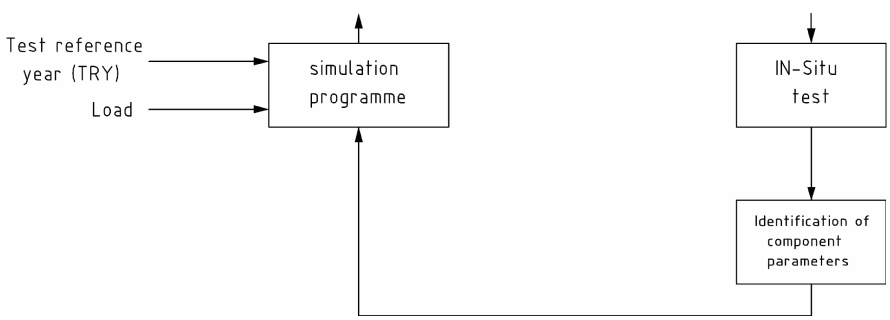
Following, the methods proposed for the *short-term system testings* are reported. The objective of the two short-term system tests, presented in **Annex C** of the EN 12977-2 Standard, is the characterization of system performance and/or the estimation of the ability of the system to deliver the energy claimed by the designer.

In principle, the approaches for *short-term system testing* are referred to:

1) Simplified check of short-term system performance, carried out by intercomparison of the measured thermal solar system heat gain with the one predicted by simulation, using the actual weather and operating conditions as measured during the short-term test;



2) Short-term test for long-term system performance prediction. The performance of the most relevant components of the solar heating system is measured for a certain time period while the system is in normal operation.



Intercomparison of the observed and simulated energy quantities provides the indirect validation of collector and storage design parameters. The measured data within the collector array are also used for direct identification of the collector array parameters. As far the component parameters are verified, the long-term prediction of the system gain as well as the detection of possible sources of system malfunctioning are possible.

Simulation methodologies based on: the Input-Output methodology, the f-chart and the Component Testing - System Simulation (CTSS) (as TRNSYS program), taken from the relevant literature, are investigated and evaluated, by taking into consideration the specific characteristics of the method for each application.

4. Description of Simulation Methodologies

Several different simulation models, namely by Close (1967), Sheridan et al. (1967), Butz et al. (1974), Lof and Tybout (1972), Buchberg and Roulet (1968), Brinkworth (1978), etc. have developed quasi-steady state models of solar systems. These are capable of identifying important parameter trends in solar heating systems for specific designs. The most accurate and sophisticated computer simulation program is the TRNSYS and was developed at the Solar Energy Laboratory of Winsconsin-Madison. No doubt, this simulation programme gives good analysis, but it cannot be used as a design tool because of being complicate.

In this review, except of the TRNSYS simulation programme, only those methodologies that fitted properly to the aims of the performance prediction of the *large custom-build solar systems* and required simple computer calculations and / or measurements, are considered.

4.1. The Input-Output approach

4.1.1 Phenomenology of the operation of large solar thermal systems

The phenomenological investigation of the variation of the main quantities characterizing the operation of a Solar Thermal System (STS) may, by itself, help in determining their mutual dependencies and relevance.

From measurements at the Laboratory of Solar Thermal & other Energy Systems at NCSR "DEMOKRITOS", as well as from a large number of similar measurements in the relevant literature, it has been found that the typical form of the time evolution of the main quantities characterizing the behavior of a solar thermal system is as graphically represented in Fig. 1. This is the temporal evolution of the mean temperature of the working fluid in the collector field *TFm* and the mean storage tank temperature *TSm* for an initial storage water temperature *T´Si*. for any type of solar system and for a typical sunny day with instantaneous solar radiation *I*. In practice, however, the solar systems often start their daily operation at higher energy levels, due to the remaining, unused energy from the previous day.

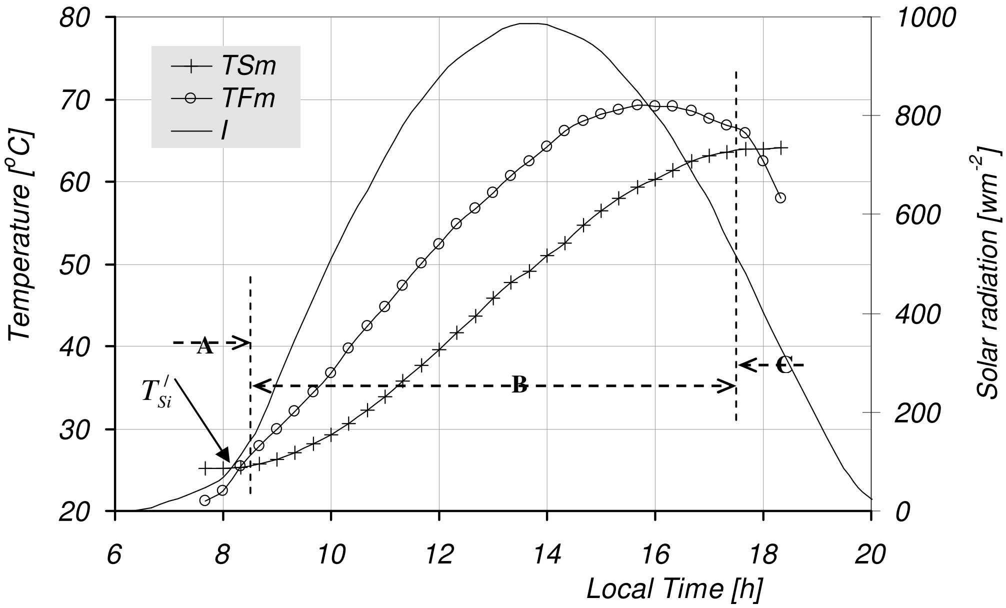


Figure 1: *Time variation of the solar radiation I, the mean storage tank temperature TSm and the mean collector-field temperature TFm, typical of a sunny day. The inertia (A), pseudo-steady state (B) and saturation (C) phases are also demarcated.*

Upon examination of the Fig. 1, it may at first be inferred that the daily operation of such systems is characterized by the presence of three distinct phases, differing to one another with respect to the evolution of the main energetic parameters:

A. the *initial inertia phase*
B. the main, from the duration point of view, phase of *pseudo-steady state*,
C. the *saturation phase*.

During the *first phase*, which starts at sunrise, the system lies in a state of inertia, i.e., without any marked change in the energy content of the storage tank, but with the working fluid temperature in the collector field increasing with respect to the tank temperature.

The *second phase* of pseudo-steady state, which is the longest in duration, is the phase during which practically the entire collection of solar energy and transfer to the storage tank takes place.Furthermore, during this phase the rate of change of both the mean tank water temperature *TSm*, as well as the mean working fluid temperature, remains almost constant. Likewise, the rate of change of the energy content of the tank water remains almost constant as well. It may, therefore, be claimed that the system lies in a pseudo-steady state from the point of view of the time variation of the energetically useful heat fluxes. Within this observation lies the basis of the I/O approach, presented below.

The *saturation phase* originates at a time instant where $dTSm/\ dt \approx 0$ in Fig. 1 and is characterized by zero (or negative, if heat losses are high) net energy input to the tank.

4.1.2 Analytical treatment of the pseudo-steady state

The analytical expressions that described the instantaneous thermal behavior of a closed-loop STS are (Klein et al., 1974 and Duffie and Beckman, 2006):

I. *Energy balance of the solar collector field*

$$\dot{Q}(t) + (MC)_{F-P}\frac{dT_{Fm}(t)}{dt} = A_F n_o k(t) I(t) - (AU)_{F-P}\left(T_{Fm}(t) - T_a(t)\right) \quad (1)$$

II. *Heat transfer in the heat exchanger*

$$\dot{Q}(t) = (UA)_{ex}\left(T_{Fm}(t) - T_{sm}(t)\right) \quad (2)$$

III. Energy balance in the storage tank

$$(MC)_s \frac{dT_{sm}(t)}{dt} = \dot{Q}(t) - (UA)_s\left(T_{sm}(t) - T_a(t)\right) \quad (3)$$

Based on the above equations, the overall energy output Q at the end of a day which is characterized by solar energy incident on the STS equal to H_d and mean ambient temperature equal to $\overline{T}_a$, and when the initial water temperature in the storage tank is equal to T_{si}, is given by the equation:

$$Q = F_1\ H\ + F_2\left(\overline{T}_a - T_{si}\right) + F_3 \quad (4)$$

As far as the physical meaning of the coefficients of Eq. 4 is concerned, the following observations may be made regarding the coefficients involved:

- F_1, as related to the solar radiation incident on the collector field, denotes in a sense the efficiency of the system, or alternatively, the effective collector-field surface
- F_2, as relating to the temperature difference between the tank and the surroundings, refers to the thermal losses of the system
- F_3 expresses the thermal inertia of the system, which depends mainly on its thermal capacitance, the overall thermal losses, as well as the energy level in the storage tank at the start of the day.

It should be noted that the determination of the coefficients F_1, F_2 and F_3 always takes into account the specific characteristics of each system. Therefore, as is common practice in solar thermal system analysis, a solar collector field is treated as an equivalent collector, the characteristic data of which are determined by taking into account the respective data of each individual collector, their interconnection mode and the flow rate of the working fluid. The interconnection mode in particular affects the overall flow rate in the collector field and, consequently, the $(UA)_{ex}$ factor of the heat exchanger involved in the equations (Duffie and Beckman, 2006).

The application of the proposed approach in the calculation of the expected energy yield of a STS by means of Eq. 4 requires the determination of suitable values for the coefficients F_1, F_2 and F_3. These coefficients are functions of the physical parameters of the solar system, the duration t_d of the day and the duration of the pseudo-steady state t_{op}, whereas, F_3 in particular, is also a function of the initial storage tank temperature $T_{si.}$ From the same equations it may be concluded that, for each particular system, the estimation of the respective suitable coefficients ought to take into account not only the system characteristics, but also the intended conditions of its use (Belessiotis et al., *Solar Energy,* 84 (2010), 245–255).

The experimentally determined or analytically calculated values of the coefficients allow the subsequent simulation of the energetic behavior of the STS over specific time periods, as well as the realistic estimation of its expected energy output.

4.1.3. Theoretical and experimental values of the coefficients F_1, F_2 and F_3

The investigation of the validity of the proposed model was based on the comparison between the analytically derived values of the coefficients F_1, F_2 and F_3 of the characteristic I/O equation with the experimental ones (Belessiotis et al., *Solar Energy* 84 (2010) 245–255).

The analytical calculation of the coefficients F_1, F_2 and F_3 can be performed with the thermal-hydraulic quantities of the collector determined according to the EN 12975-2 and ISO 9806-1 standards. Furthermore, the interconnection mode of the collectors in the field has also been considered in the calculation. For the total heat losses of the collector field, both losses from collectors and piping have to be taken into account. For the duration of the day and the pseudo-steady state, as well as for the initial tank temperature the actual respective values observed during the measurement period used.

For the determination of the experimental values of the coefficients F_1, F_2 and F_3, extensive measurements over a period of relatively small time have to be performed, during which the system have to be subjected to diurnal operating cycles characterized by a full draw-off of the accumulated energy at the end of the day. For each day of operation, the energy supplied to the storage tank Q_{meas}, the temperature difference $(\overline{T}_a - T_{si})_{\exp}$ and the daily total incident solar radiation H at the collector level have to be, among other quantities, estimated. From the entire set of measurements a number of days have to be selected, aiming at outlining the systems behavior over a wide condition range (different seasons, different levels of solar radiation, different temperature-difference values). The estimation of the coefficients was achieved by means of the multi-factor least-squares method.

Table 1: *Technical specifications of the systems used for validation*

Quantity	Value		Units
	System 1	System 2	
Collector aperture area, A_c	1.78	2.59	m^2
Maximum collector efficiency, n_0	0.757	0.732	-
Overall collector heat loss coefficient, U_c	5.292	4.455	$Wm^{-2}K^{-1}$
Effective thermal capacity of collector, $(MC)_c$	16	29	kJK^{-1}
Water content in collector, W_w	4.5	5.8	*kg*
Number of collectors in the field, *Nc*	40	48	-
Heat-exchanger overall heat transfer coefficient, $(UA)_{ex}$	2500	13300	WK^{-1}
Storage tank volume, V_s	5000	32000	*l*
Overall storage-tank heat loss coefficient, $(AU)_s$	30	150	WK^{-1}

Table 2: *Values of the coefficients F_1, F_2 and F_3 theoretically obtained*

	F_1 [m^2]	F_2 [MJK^{-1}]	F_3 [MJ]
System 1	29.8	12.2	17.5
System 2	68.5	20.7	6.4

Table 3: *Values of the coefficients F_1, F_2 and F_3 experimentally obtained*

	F_1 [m^2]	F_2 [MJK^{-1}]	F_3 [MJ]
System 1	27.85	10.82	43.57
System 2	63.68	21.07	27.56

The comparison has been attempted on two large solar thermal systems, the main features of which are shown in Table 1. Given the importance of the temperature level in the storage tank for the proposed modeling approach, two typical STS were selected, the first one (System 1) with a fully-mixed tank and the second one (System 2) with a fully-stratified tank. Based on the above, the theoretical estimates for the values of the coefficients shown in Table 2.

4.1.4. *Comparison between results obtained using experimental and theoretical values of the coefficients*

In Figure 3 and 4 comparisons between the experimental and the theoretical values, predicted by the model, for the daily output of the above mentioned two systems are graphically depicted against measured data. In order to obtain the daily output yield experimentally and theoretically derived values of the coefficients was used respectively. The evaluation was attempted for both systems, by employing typical meteorological data for the Athens region.

The observation of the macroscopic operational parameters of a typical solar thermal system during its pseudo-steady state, which extends over almost the entire active period of the system, has allowed the theoretical foundation of the I/O approach as a valid model for predicting the daily energetic behavior of a STS. This approach is characterized primarily be the consideration of the system as a functionally integral set, the daily energetic behavior of which may be described by a characteristic I/O equation.

An investigation towards a further validation of the method is at this moment in press (Belessiotis et al., *Ren. Energy*, in press). According to this investigation the I/O method describes in a very satisfactory manner the daily energy performance of large solar thermal systems, as may be concluded from the high values of the correlation coefficient, R^2, but also from the low values of the standard simulation error, σQ, which is of the order of 5%, a value which is quite satisfactory for this type of models.

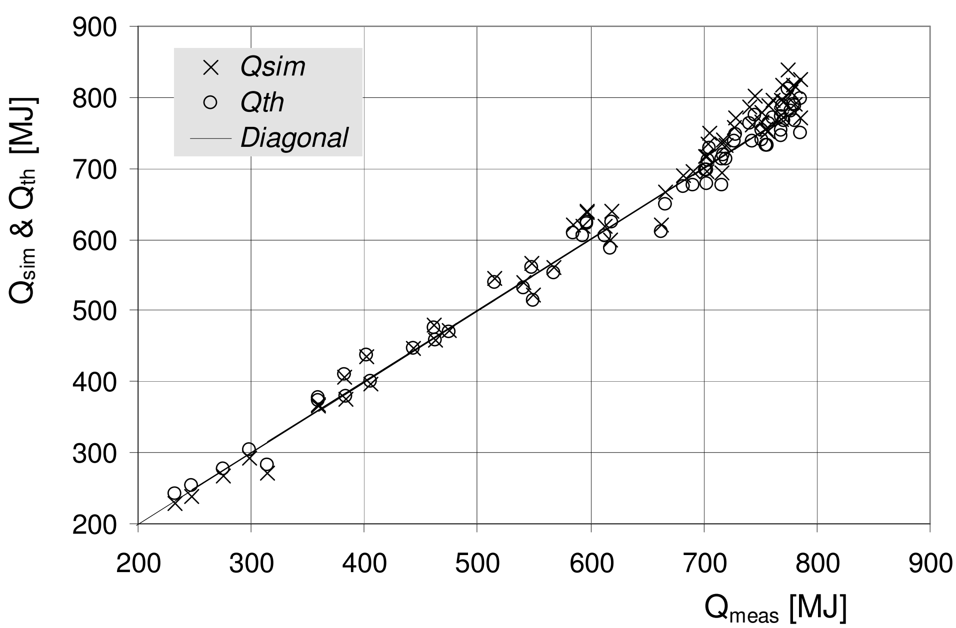


Figure 3: *Comparison of* the *simulated (Q_{sim}) and theoretical (Q_{th}) values of the energy output against the experimental one (Q_{meas}) for System 1.*

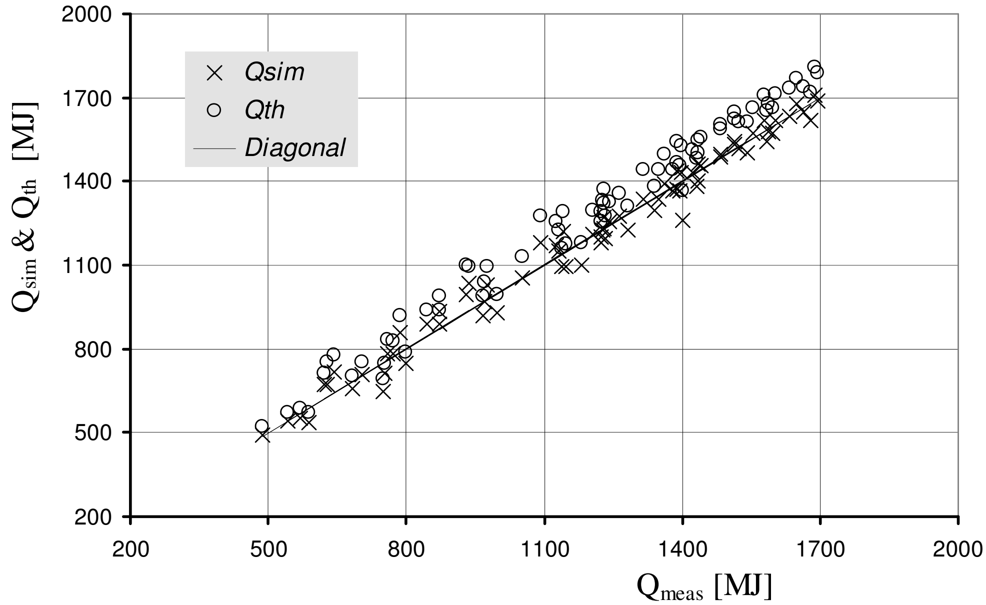


Figure 4: *Comparison of the simulated (Q_{sim}) and theoretical (Q_{th}) values of the energy output against the experimental one (Q_{meas}) for System 2.*

The coefficients of the I/O equation are characterized by relatively small standard deviations, except for the constant term F_o. The high values of covariance among the coefficients observed can be interpreted as an indication of strong mutual dependence among the calculated values. The very strong dependence of the coefficient F_H on F_o, in conjunction with the high standard deviations of the latter, lead to the conclusion that in certain cases F_o can be considered as almost vanishing. This can occur when the average operating temperature of the solar field TF_m , at the start of its operation is of the same magnitude as the initial water temperature in the tank, T_{Sin}. In this case, it is recommended that the determination of the coefficients F_H and F_T be performed based on the two-coefficient model, without the use of the constant term F_o, attaining, thus, considerably smaller standard deviations.

4.2. The f-chart method

The f-Chart method is an analysis that is useful for the design of active and passive solar heating systems, especially for selecting the size and type of solar collectors supplying the DHW and heating loads. It was originally developed as part of the Dr. Sanford Klein's Ph.D. thesis, entitled "A Design Procedure for Solar Heating Systems" (1976), Klein et al. (1976a, 1977). The f-Chart method consists of correlations of the results of a large number of detailed simulations using TRNSYS, a transient systems simulation program by Klein et al. (1973).

The method requires two values to describe a solar collector: *the solar collector thermal performance curve slope* (F_RU_L, W/m2K) and *intercept* ($F_R(\tau\alpha)$, %) from standard collector tests. These parameters include the F_R (Collector Efficiency Factor), U_L (Collector Overall Energy Loss Coefficient) and $\tau\alpha$ (Transmittance-Absorptance Product). F_RU_L and $F_R(\tau\alpha)$, were initially introduced by Whillier (1953). These parameters were also by Hottel and Whillier (1955), and Liu and Jordan (1963) in conjunction with the development of the φ concept (utilizability), which calculates the fraction of the total month's incident radiation on a horizontal surface.

The φ concept was subsequently developed by Whillier (1953), as location-dependent, monthly-average hourly utilizability. Liu and Jordan (1963) then generalized the Whillier's φ concept to location-independent monthly average hourly utilizability.

4.2.1 Basic equations of the f-chart method

The *f*-chart method is as mentioned before a correlation of the results of many hundreds of thermal performance simulations of solar heating systems. The resulting simulations give *f*, the fraction of the monthly heating load (for space heating and hot water) supplied by solar energy as a function of two dimensionless parameters, *X* (Collector Loss) and *Y* (Collector Gain). *X* is related to the ratio of collector losses to heating loads, and *Y* is related to the ratio of absorbed solar radiation to the heating loads (Duffie, J.A., Beckman, W.A., 2006).

$$X = F_R\, U_L \times \frac{F'_R}{F_R} \times \left(T_{ref} - \bar{T}_a\right) \times \Delta\tau \times \frac{A_C}{L} \quad (5)$$

$$X = F_R\, (\tau\alpha)_n \times \frac{F'_R}{F_R} \times \frac{(\overline{\tau\alpha})}{(\tau\alpha)_n} \times \bar{H}_T N \times \frac{A_C}{L} \quad (6)$$

where

A_c	=	Area of solar collector (m^2 or ft^2),
F'_R	=	Collector-heat exchanger efficiency factor (%),
F_R	=	Collector heat removal factor (%),
U_L	=	Collector overall energy loss coefficient (W/m^2-°C),
$\Delta\tau$	=	Total number of seconds (SI) or hours (IP) in the month,

T_a	=	Monthly average ambient temperature (°C),
L	=	Monthly total heating load for space heating and hot water (GJ),
H_T	=	Monthly averaged, daily radiation incident on collector surface per unit area (MJ/m^2),
N	=	Number of days in the month,
$(\tau\alpha)$	=	Monthly average transmittance-absorptance product (%),
$(\tau\alpha)_n$	=	Normal transmittance-absorptance product (%), and
T_{ref}	=	An empirically derived reference temperature (100 °C).

The f-chart equation for the fraction *f* of the monthly water heating loads supplied by solar energy for a liquid system is the following:

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \quad (7)$$

which is valid for $0 < X < 18$ and $0 < Y < 3$.

The ratio $\frac{F_R'}{F_R}$ takes into account the losses in the heat exchanger between the collector circuit and the consumption circuit

$$\frac{F_R'}{F_R} = \left(1 + \frac{F_R U_L A_C}{\dot{m}c_p}\left(\frac{\dot{m}c_p}{\varepsilon_C C_{min}} - 1\right)\right)^{-1} \quad (8)$$

with: ε_C = heat-exchanger effectiveness

The fraction F of the annual heating load supplied by solar energy is the sum of the monthly solar energy contributions divided by the annual load.

$$F = \sum (f \cdot L) \Big/ \sum L \quad (9)$$

4.2.2 Application and validation of the f-chart method

The f-chart method can be used to estimate, among others, the long-term average performance of the water storage heating systems, building storage heating systems, domestic water heating systems, integral collector-storage DHW, passive collector-storage etc. Can also evaluate the performance of systems consisted either of flat-plate collectors, evacuated tubes type as well as of the Parabolic Concentrating type.

One of the first assessments of the accuracy of the f-chart method was performed by Klein as part of his Ph.D. thesis (Klein 1976). In this assessment Klein showed that the values of $F_R(\tau\alpha)$ were 0.663 from measurement data recorded during 1974 in Madison, Wisconsin, and 0.628 from calculation, which is only a 5.3% deviation from experiment. The values of $F_R U_L$ were 20.5 from experiment data and 19.9 from calculation, which was only a 2.9% deviation from experiment data.

In Klein et al., (1976), compared the results of the f-chart with the measurement data from Engebretson (1964) on the MIT House IV in Blue Hills, Massachusetts, for the periods of 1959-60 and 1960-61. In their analysis the yearly average value of the solar fraction estimated by the f-chart method was only 8% higher than the measured values for the 1959-60 heating season and 5% higher for 1960-61.

Fanney and Liu (1980) showed the comparison between experimental and computer predicted performance for solar hot water systems. Their measurements were from experiments performed at the National Bureau of Standards (NBS) in Gaithersburg, Maryland, for the period of July 1978 to June 1979. In their paper showed that the deviation between the f-chart values of tilted surface solar radiance based on measured horizontal surface solar irradiance and measured values of tilted surface solar radiance is about 8% in average for the period.

Duffie and Mitchell (1983) performed a comparison study between f-chart simulation data and measurement data from measurements taken by the NBS and the National Solar Data Network (NSDN) in over 30 cities located different climate regions. Results showed that twenty-two of the thirty cities showed that the simulations matched the measurement within ±15% of the f-chart prediction values.

Fanney and Klein (1983) conducted a study of the performance of solar domestic hot water systems at NBS in Gaithersburg, Maryland, for the year 1980. In their study they compared on-site measurements with predictions from f-chart. Their study showed that the annual solar savings fraction estimated by f-chart method was within 5 % of the measured value for the five active systems.

Barley and Winn (1978) used the f-chart method as a verification tool to test the accuracy of a method they developed for sizing optimal solar collectors. In their report they showed good agreement with the f-chart calculation, showing the deviations of less than 3%.

Drew and Selvage (1979) performed a comparison study between f-chart and the Simplified Load Ratio (SLR) method developed by Balcomb and McFarland (1978). Their results indicated a discrepancy of 9% solar fraction between the two methods, SLR and f-chart.

Sfeir (1980) developed a stochastic model for predicting solar system performance. In this study annual solar energy as a function of collector area was compared to the f-chart results. This study showed that the largest difference between curves generated from the two different methods did not exceed 4% (or 2.5% of the annual load).

Chang and Minardi (1980) developed an optimization formulation for solar heating systems. In their study the results of the optimum collector areas from f-chart and their model was displayed graphically. Although the graph showed good agreement between the two methods, their published study stopped short of providing any quantitative values for the comparison.

Hawas and Abou-Zeid (1983) developed a general chart (R-Chart) for sizing collectors of solar heating systems and compared their results with those from f-chart. They concluded that the results of their R-Chart method have a good agreement with the f-chart method in all cases. However, in a similar fashion as the paper by Chang and Minardi (1980), their paper stopped short of providing any quantitative values for the comparison.

Ajona and Gordon (1987) developed an analytic model for the long-term performance of solar air heating systems and showed the comparison with the f-chart method. The comparison of results for the annual solar fraction (f) calculated with their analytic model and those corresponding f-chart results was also presented graphically. However, their paper also stopped short of providing any quantitative values for the comparison.

Tsilingiris (1996) also developed an analytic model for the solar water-heating design. The results from his analytic model were compared with those from the f-chart method, and the comparison indicated very good agreement between results from his model and f-chart method. However, his paper also stopped short of providing any quantitative values for the comparison.

In the studies above reported, comparing solar system performance predicted by f-chart against data from measurements, an agreement in the 2 to 15% range was showed. From the other hand the f-chart method has often been used as a standard to compare new methods against noting that f-chart is widely used as a standard. In those studies that were reviewed, agreement varied from 2.5% to 9%, with several studies reporting only graphical comparisons, or qualitative assessments such as “good agreement”, or “excellent agreement”.

4.3. The TRNSYS program

4.3.1 Basic concepts of the TRNSYS simulation program

TRNSYS is an acronym for a 'transient simulation' which is a quasi-steady simulation model. This program, which is a modular differential equation solver, was developed by the members of the Solar Energy Laboratory by the University of Wisconsin-Madison to be a general purpose engineering problem solver (Klein et al. 1973). The program consists of many subroutines that model subsystem components. The mathematical models for the subsystem components are given in terms of their ordinary differential or algebraic equations.

With a program such as TRNSYS which has the capability of interconnecting system components in any desired manner, solving differential equations and facilitating information output, the entire problem of system simulation reduces to a problem of identifying all the components that comprise the particular system and formulating a general mathematical description of each. Once all the components of the system have been identified and a mathematical description of each component is available, it is necessary to construct an information flow diagram for the system. The purpose of the information flow diagram is to facilitate identification of the components and the flow of information between them.

Each component is represented as a box, which requires a number of constant parameters and time dependent inputs and produces time dependent outputs. An information flow diagram shows the manner in which all system components are interconnected. A given output may be used as an input to any number of other components. From the flow diagram a deck file has to be constructed containing information on all the components of the system, weather data file, and the output format. Subsystem components in the TRNSYS include solar collectors, differential controllers, pumps, auxiliary heaters, heating and cooling loads, thermostats, pebble-bed storage, relief valves, hot water cylinders, heat pumps and many more. There are also subroutines for processing radiation data, performing integrations, and handling input and output. Time steps down to 1/1000 h (3.6 s) can be used for reading weather data which makes the program very flexible with respect to using measured data in simulations. The users can have a variety of outputs from their simulations, including: the calculated solar fraction, auxiliary heating requirement, and many other component-level performance indices.

More details about TRNSYS program can be found in the program manual. There are numerous applications of the program in literature comprising thermosyphon system, modeling and performance evaluation of solar domestic hot water system, investigation of the effect of load profile, modeling of industrial process heat applications and modeling and simulation of absorption system.

4.3.2 Application and validation of the TRNSYS simulation program

Several validation studies have been conducted since 1976 (Duong and Winn 1977; and Mitchell et al. 1978) in order to determine the degree to which the TRNSYS program serves as a valid simulation program for a physical system. It has been shown by analyzing the results of this validation studies that the TRNSYS program provides results with a mean error between the simulation results and the measured results on actual operating systems under 10%. System simulations using specially constructed TRNSYS input files have been compared with experiments for several periods of operation of the Colorado State University (CSU). In these simulations the predicted collector output using TRNSYS agreed with the experimental output within 5%. Furthermore, the heat transferred across the air heater was compared with that delivered by the auxiliary heater and agreed to within 6% of measured values.

The use of TRNSYS for the modeling of a thermosyphon SWH was also validated and found to be accurate within 4.7%.

It can be seen from the literature that, hourly TRNSYS simulations versus measured data were shown to be within 5 to 6%, and f-chart predictions versus TRNSYS simulations were shown to vary from 1.1% to 4.7%.

Klein, (1976), compared prediction results between f-chart and TRNSYS simulation as part of this Ph.D. work. His results show that the standard deviation between those two methods was 3.7% for the liquid system and 3.3% for the air system.

Klein and Beckman (1979) presented a general design method for closed-loop solar thermal energy systems. In this project they performed a study of the comparison of TRNSYS, f-chart, and $\overline{\Phi}$, f-chart results from six different cities in U.S. and showed that the annual solar load fractions were 0.59, 0.59, and 0.61, respectively, which indicates that the results from the three methods are in good agreement. In the comparison of monthly solar load fractions performed for Madison, Wisconsin, it was shown that the three methods match each other with a difference of only 4.4%.

Evans et al. (1985) implemented the f-chart method in the European climates. In their study they showed that the design method performance predictions for domestic hot water system were within an RMS error of 2.2% of the simulation results. RMS errors of the system performance were estimated to be 4.7% for air systems and 4.2% for liquid systems.

Ammar et al. (1989) investigated optimum parameters for solar domestic hot water systems in Alexandria, Egypt. In their study they compared results from f-chart and a TRNSYS simulation. They showed that the annual solar fraction predicted by the f-chart method was only 1.1% different from the value obtained from TRNSYS.

Minnerly et al. (1991) simulated the annual performance of the equivalent simplified system using f-chart. In their study they showed an RMS difference of 2.2% between the simulated performance of TRNSYS and f-chart.

In summary, in the above reported studies, comparing f-chart and TRNSYS simulations of the same system, good agreement was showed, varying from 1.1% to 4.7%, which is slightly better than the results of f-chart versus measured data. This is expected since the comparison of correlation (which is based on simulations) against a simulation should give better results than either method compared against measured data that contains unavoidable experimental error.

Therefore, according to these studies it can be concluded that a properly constructed TRNSYS simulation can be a valid and reliable tool for the analysis and design of solar systems (Garg 1985).

4.4. Summary of the reviewed methods

The ability of the proposed input-output method to describe the daily energetic behavior of large-scale, central solar systems has been experimentally validated, using measurement data over large time periods in two typical solar thermal systems, differing from each other in the level of stratification in their respective storage tanks. The analytically calculated coefficients of the characteristic I/O equation of the systems were found to be in good agreement with those obtained from the experimental measurements. The results of the experimental validation of the model are considered as particularly satisfactory, taking into account the low level of complexity of the proposed methodology.

The reported accuracy of the *f-chart method* has been assessed by reviewing the related accuracy of *TRNSYS simulations* versus measured data, f-chart predictions versus measured data, f-chart predictions versus TRNSYS simulations and f-chart predictions versus other methods. In summary, hourly TRNSYS simulations versus measured data were shown to be within 5 to 6%, f-chart predictions versus measured data showed agreement in the 2 to 15% range, and f-chart predictions versus TRNSYS simulations were shown to vary from 1.1% to 4.7%. A significant number of studies used f-chart to assess the accuracy of newly developed methods. In these studies agreement varied from 2.5% to 9%.

5. Conclusions

The *input-output modeling method* allows the prediction of the energetic performance of large solar thermal systems by means of two approaches which are mutually related in their underlying theory and may be used in a complementary fashion, even though they differ in their practical implementation:

- ***Simplified check of short-term system performance.*** According to the first means of implementation, similar to the common practice of process modeling, the coefficients of the characteristic equation of the model may be calculated as a function of the physical parameters of an installation, taking into account the expected operating conditions, in which case the application of the method may also concern the design and/or optimization of such systems.
- ***Short-term test for long-term system performance prediction***. The second means of implementation consists of the identification of the coefficients of the characteristic I/O equation using suitable experimental data obtained on an existing system, which may be treated as a black box, without, that is, the requirement that the technical features of its individual components be known.

TRNSYS simulation program and f-chart method both allows the prediction of the energetic performance of a *large custom-build solar thermal system* by means of the ***simplified check of short-term system performance*.** The coefficients of the characteristic equation of the method may be calculated as a function of the physical parameters of the installation, taking into account the expected operating conditions, in which case the application of the method may also concern the design and/or optimization of such systems.

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