THE DEVELOPMENT OF MATHEMATICALLY HIGHLY CONDENSED COMPUTER SIMULATION MODELS

task VI

December 1992

INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

THE INTERNATIONAL ENERGY AGENCY
SOLAR HEATING AND COOLING PROGRAMME

International Energy Agency

The International Energy Agency, headquartered in Paris, was formed in November 1974 as an autonomous body within the framework of the Organization for Economic Cooperation and Development to establish cooperation in the area of energy policy. Twenty-one countries are presently members, with the Commission of the European Communities participating under a special arrangement.

Collaboration in the research, development and demonstration of new energy technologies to help reduce dependence on oil and to increase long-term energy security has been an important part of the Agency's programme. The IEA R&D activities are headed by the Committee on Research and Development (CDR) which is supported by a small Secretariat staff. In addition four Working Parties (in Conservation, Fossil Fuels, Renewable Energy and Fusion) are charged with monitoring the various collaborative energy Agreements, identifying new areas for cooperation and advising the CRD on policy matters.

Solar Heating and Cooling Programme

One of the first collaborative R&D agreements was the IEA Solar Heating and Cooling Programme which was initiated in 1977 to conduct joint projects in active and passive solar technologies, primarily for building applications. The eighteen members of the Programme are:

Australia	Germany	Norway
Austria	Finland	Spain
Belgium	Italy	Sweden
Canada	Japan	Switzerland
Denmark	The Netherlands	United Kingdom
European Community	New Zealand	United States

A total of sixteen projects or "Tasks" have been undertaken since the beginning of the Programme. The overall programme is managed by an Executive Committee composed of one representative from each of the member countries, while the leadership and management of the individual Tasks is the responsibility of Operating Agents. These Tasks and their respective Operating Agents are:

*Task 1: Investigation of the Performance of Solar Heating and Cooling Systems- Denmark
*Task 2: Coordination of Research and Development on Solar Heating and Cooling - Japan
*Task 3: Performance Testing of Solar Collectors - United Kingdom
*Task 4: Development of an Insulation Handbook and Instrument Package - United States
*Task 5: Use of Existing Meteorological Information for Solar Energy Application - Sweden
*Task 6: Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors - United States
*Task 7: Central Solar Heating Plants with Seasonal Storage - Sweden
*Task 8: Passive and Hybrid Solar Low Energy Buildings - United States
*Task 9: Solar Radiation and Pyranometry Studies - Federal Republic of Germany
Task 10: Material Research and Testing - Japan
Task 11: Passive and Hybrid Solar Commercial Buildings - Switzerland
Task 12: Building Energy Analysis and Design Tools for Solar Applications - United States
Task 13: Advanced Solar Low Energy Buildings - Norway
Task 14: Advanced Active Solar Systems - Canada
Task 15: Advanced Central Solar Heating Plants (In Planning Stage)
Task 16: Photovoltaics in Buildings - Germany
Task 17: Measuring and Modeling Spectral Radiation - Germany
Task 18: Advanced Glazings and Associated Materials for Solar and Building Applications - UK

*Completed Task

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by

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Abstract

The cooperative work of the International Energy Agency (IEA) on evacuated collector systems (IEA Solar Heating & Cooling Programme, TASK VI: Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors) covered both experimental and analytical activities on various active solar energy systems, ranging from small domestic hot water to large industrial process heat and district heating plants. During the investigations strong experimental evidence was found that universal system characteristics of the respective installations exist, which may be used for "simplified modelling". Thus investigations of these characteristics were performed with the objective to generate them by analytical approach. Originally only the so-called energy Input-/Output-Diagrams were considered, which connect the thermal output of the system with the daily or monthly incident radiation sum. However, in the course of the investigations it was shown that similar characteristics exist for various other values such as solar fraction, maximum temperature, auxiliary and parasitic energy, and others. It has been furthermore shown that for the ample determination of system characteristics complex and detailed models are needed. Thus the originally chosen term of "simplified" models was replaced by "mathematically condensed" ones, as those models condense the information to a few elementary equations.

Most of the programmes which evolved from these investigations are user-friendly, offer a novel family of accurate and fast design methods, and provide a good understanding of complex systems. Two of these programmes (i. e. ISFH/chapter 7 and G^3/chapter 5) are available to the public and are used in practice for research and design purposes. Information on ordering these programmes is found in Chapter 3.

Abbreviations

Ac	collector aperture area
CPC	compound parabolic concentrator
DH	district heating
DHW	domestic hot water preparation
DL	length of day (hrs.)
DT	mean operational, energy weighted temperature difference (absorber minus ambient)
ETC	evacuated tubular collector
ETC/iCPC	evacuated tubular collector with internal CPC
FPC	flat plate collector
H001	daily total radiation sum onto collector plane
H009	total radiation sum onto collector plane of preceding day
IEA SH&C	International Energy Agency, Solar Heating and Cooling Programme
IOD	Input-/Output-Diagram
IPH	industrial process heat preparation
PTC	parabolic trough collector
Q102	daily thermal output of collector system (incl. piping)
Q112	daily thermal collector output
SH	space heating
SOC	system operational characteristic
Task VI	IEA SH&C, Task VI: The Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors
TASK XIV	IEA SH&C, Task XIV: Advanced Active Solar Energy Systems
TMY	Typical Meteorological Year (data tapes with meteorological values for "typical" years in hourly sequence)
U	thermal loss factor (W/(m^2*K))
$\tau\alpha$	effective optical collector efficiency with normal insolation
λ	thermal conductivity (W/(m *K))

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0. Preface

This report has a two-fold purpose. The original intention was to document the IEA Solar Heating and Cooling Task VI work on simplified models, which centered on Input-/Output (I/O)-based methods. However, in the course of model development and improvement, these methods became more sophisticated, complicated, and detailed, so that now the most highly developed one has a level of sophistication comparable to most "detailed" programmes. Thus the term "simplified" is not longer applicable to all these models. Yet, as they center generally on the operational behavior of complete systems, they may be called mathematically "compressed" or "condensed" models. Though some of them are no longer simple in structure, they are usually simple in application and they base on the experimentally determined and analytically validated outcome, that for an accurate determination of the most important features of a solar installation (e.g. solar to load, solar fraction, extreme conditions, surplus energy, and others) a lengthy hour-by-hour, day-by-day calculation is no longer necessary. Thus we intend

- to show that universal, system related characteristics exist, by which the determination of the collector output and quite a few other interesting factors are easily determined on a daily, monthly, and annual basis
- to show that this approach implies - if properly performed - only insignificant errors,
- to present possible methods to determine these system characteristics,
- to document and explain different approaches of the Task VI participants in this or related areas, and
- to show some applications, performance extrapolations, and conclusions.

Beside these I/O-based methods there were quite a few other approaches. Modelling active solar systems in a detailed manner has been an ongoing major activity as well at DLR, Stuttgart, Germany, Colorado State University, Ft. Collins, USA, and University of Waterloo, Canada, since the early or mid-seventies. The newer Task VI related activities in this area are documented in a special report (/1 /). Further activities were carried out in the early eighties at the University of Eindhoven, The Netherlands and resulted in a simple programme for hand-held computers (/2/). However, as this is basically an isolated development, not showing major connections to the other Task VI activities in the field, it will not be treated within this report.

Eventually there were some Australian simulation activities, which ended in a simplified method determining the system behavior directly - i. e. in only one step - on an annual basis (/3/). However, as Australia withdraw from the Task VI activities in 1986 and there is only a short paper available, we restrict ourselves to a brief mention of this work.

1. Simulation Models and the Principle of Mathematical Condensation

Elements, Components, Systems . Understanding and Modelling of Complex Systems • System's Behavior

The world is organized in a hierarchy of systems with increasing complexity. From the view of quarks a proton may be treated as the relevant system, from that of a galaxy clusters and superclusters of them. The "systems" of any level are the components of the next. Everything is an element in a large system, a component in a medium sized one, and a system for itself. Thus the often used classification of elements, components, and systems, is valid only from one single point of view and may, at least sometimes, obscure the real connections.

The complete understanding of a system is only possible if the processes and interactions of the respective lower levels are clearly understood. However, it is not necessary to take into account all those processes and interactions to model it sufficiently. Comprehensive characteristics, equations, and values may be sufficient for modelling purposes. Thus the respective **models are always "simplified" or "condensed".** The relevant features of the various components are represented by mathematical equations combining the external forces and conditions with the internal status, parameters, and connections to give the response of the system. This response may be, furthermore, condensed to create the characteristics of the whole system. The respective mathematical model is never complete, but reduced to the interesting features. For example the exact knowledge of the Fermi levels in a semiconductive absorbing layer is not necessary to determine the characteristics of a collector equipped with this layer; this may be done with similar accuracy with the values for the solar absorptivity and the relevant emissivity, especially if secondary effects as e.g. the incidence angle or temperature dependence are taken into account.

Coming to solar energy applications we use generally finite element/finite differences methods to model the lowest (i.e. subcomponent) level, methods which are able to handle even very complex problems, but needing the "brute force" of large supercomputers. Thus the application of those models is limited to only a few, very special cases, where the investigated processes are either too complex or too difficult to be described by comprehensive equations. A typical example are non-linear dynamic processes. One first step of mathematical condensation or compression is generally the transition to the component level, where the various components are represented by their relevant characteristic values and curves and are connected to the remaining ones according to the system schematics. It is often believed that this procedure is merely logical, but it has always to be kept in mind that in reality this is a major abstraction, as those "components" are complex systems for themselves and their operational behavior is only incompletely described by the respective equations, even if they take into account both steady-state and dynamic conditions. Thus this step includes inevitably a loss of information, but which is not considered to be a serious one. As the resulting methods lead generally to accurate and trustworthy results both in the field of research and application, they are accepted on a wide scale. They are primarily suited for comprehensive calculations such as the investigation of the prospects and the limitations of the investigated technology, for the determination of trends and the performance of "typical" systems, for special effects, and new systems. They have been fully investigated, developed, and applied by the Task VI participants and are treated in a separate publication (/1/). Nevertheless, these methods are still quite complicated, unfit for lengthy parameter variations and offer often unnecessary information as e.g. the temporary thermal stratification in a storage tank or the instantaneous value of the parasitic power. In most cases only a few values such as total solar to load, solar fraction, auxiliary energy, extreme values, etc. are really needed to design and assess an installation. These values, however, may be obtained with a similar accuracy by system based methods which originate from component based ones by a second mathematical compression, using system instead of component characteristics. Mathematical compression, if properly effected, means not a loss of accuracy, but a loss of - mostly unneeded - information.

An schematic illustration of those different approaches is shown in fig. 1.1. **Element Oriented Modelling (EOM)** covers all possible information within a system (illustrated by the number of arrows), but the procedure is very slow (numerous steps from state 'A' to state "B"). **Component Oriented Modelling (COM)** reduces considerably the amount of information, but the calculation work is similarly substantially decreased. Finally, with **System Oriented Modelling (SOM),** the information is generally compressed into one single value, but the result needs only one or some few steps. Hence, if more values are needed to assess a system, different sets of system equations are needed to determine the respective variables.

However, system based modelling is surely more abstract than the other approaches. The transition of a system between different states is defined by a complex set of equations. If the system is reproducible, it will always pass from the same initial state 'A' to the same final state "B", if the initial conditions and the external forces are identical. If the initial conditions and/or the driving forces differ, then the final state of the system may be defined by means of the derivatives of the system equations, if those derivatives really exist. If, for instance, the feature of interest is Y_a, depending on the variables X_1, x_2, x_3, ... , then the transition

$$Y_a(X_1, x_2, x_3, ...) \; ---> \; Y_a(X_1 + dX_1, X_2 + dX_2, X_3 + dX_3, ...)$$

should perform smoothly. With solar energy systems the interesting values - e. g. energy output, solar to load, maximum temperatures, etc. - are more or less all integrated values (which means that unsteady effects are virtually levelled out) and the remaining unsteadiness is mostly due to step functions of the control system. Hence, if the system equations are derived from the investigated system itself, if furthermore the relevant initial conditions are all taken into account and the deviation of the real driving forces from the anticipated ones are minor, then a good description of the system transitions and the final state should be possible by means of System Opera-

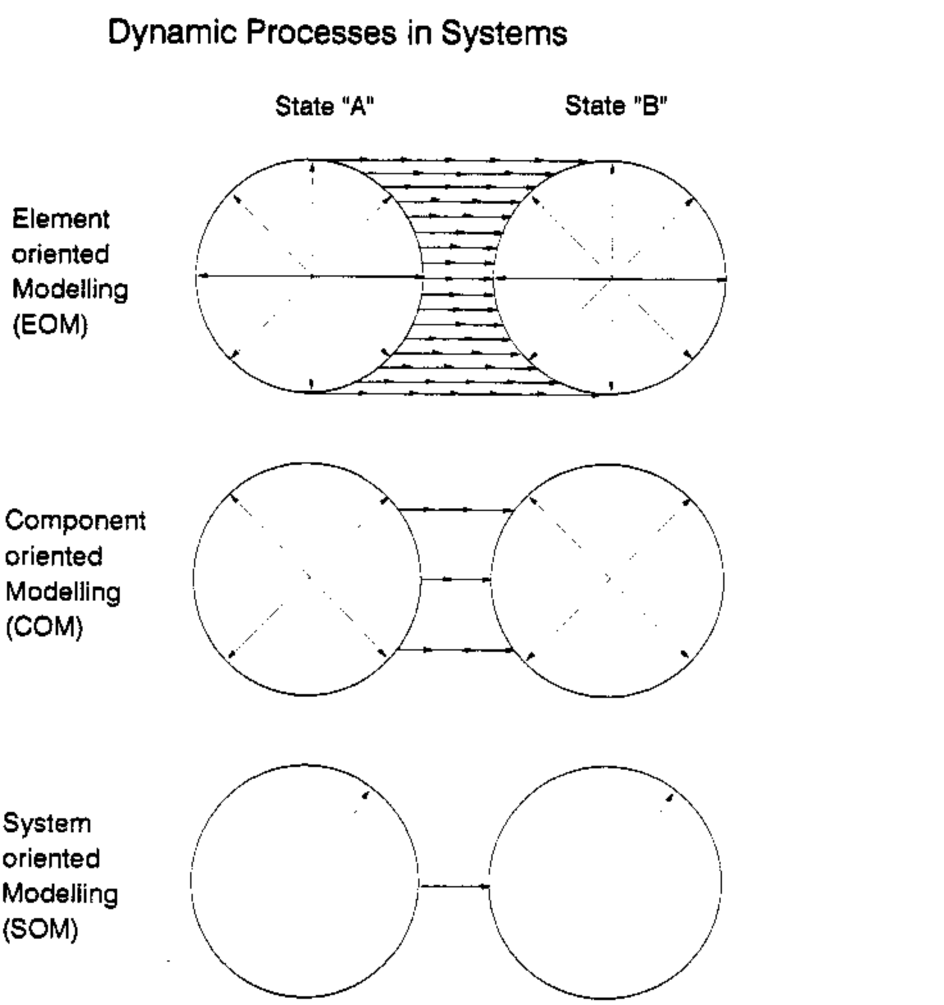


Fig. 1.1 Schematics of Different Modelling Approaches

tional Characteristics **(SOCs). Thus we define a System Operational Characteristic (SOC) as a comprehensive function which determines directly - i. e. without lengthy intermediate calculations - one specified feature of the system after an extended operation period.** Other features may be determined by similar SOCs.

One important requirement for the practical application of SOCs is that they should be virtually invariant to other, "weak" parameters as e. g. the shape of the radiation curve or that of the consumer demand, etc.. Thus some important aspects of the system may be accurately determined with only a few "strong" parameters of influence, the equations are less complex, and the calculation time is substantially reduced. If, furthermore, the investigated aspect is a daily, monthly, or annual value (e.g. the collector output) and the "strong" parameters are either mean values (e.g. mean daily ambient temperature), integral values (e.g. radiation sums), or particular instantaneous values (e.g. initial mean tank temperature), then the whole calculation may be reduced to only a few equations. Parameter variations are then a matter of seconds with a fast microcomputer.

The SOCs themselves may be obtained either experimentally and are then restricted more or less to the investigated installation and operational conditions; or analytically and may then cover a wide range of system schematics, components, applications, and climatic regions. The analytic determination of the SOCs, however, needs a comprehensive and detailed component based programme, which may be even extended by some finite element subprogrammes to derive the respective component characteristics. Thus consistent system based modelling methods are always strongly connected to and base on detailed component models. This mixture of different models is surely the most promising concept, as it combines high accuracy with low calculation time, and we are convinced that sooner or later most modelling concepts will follow this path, given by

- **determination of the Component Characteristics** in a very detailed manner, if needed by finite element methods and subsequent statistical analyses,
- **determination of the System Operational Characteristics** with a limited number of "typical" days in "typical" operation and subsequent statistical analysis,
- **application of the System Operational Characteristics** to a "real" system to determine its long term behavior.

Hence - in slightly different form - the intention of this paper may be described as

- **to show** the existence of comprehensive SOCs for most active solar energy systems,
- **to determine** those characteristics for various installations (comprising solar DHW, SH, DH, and IPH systems) and a wide field of components, schematics, and climatic regions by means of detailed, component based methods,
- **to demonstrate** how those characteristics are used to determine the main features of interest as solar fraction, solar to load, auxiliary energy, maximum temperatures etc. for typical applications,
- **to prove** the accuracy of the results by checking them against those of a detailed, component based method (TRNSYS).

Examples for these different levels of mathematical compression are given in the next three figures. Fig. 1.2 (/4/) shows the course of the collector outlet minus inlet temperature difference after the collector pump is switched on and the system is either operated with a bypass or coupled by an heat exchanger to the storage tank. An example for a "component method" is shown in fig. 1.3, where the lapse of four temperatures within the preheat tank of the "Solarhaus Freiburg" installation is plotted for a period of five days (/5/). While during heating by solar the tank temperature is uniform, during night a distinct stratification develops, with the incoming cold water reaching the lower parts of the tank first. The first, fourth, and fifth day were sunny ones, whereas the second and third one were rainy. The measured temperatures are shown by full and the modelled ones by dotted lines. The differences are mostly due to the effect that the sensor location is not identical in reality and in modelling. Thus, when a front of cold water rises from the bottom of the tank, it may reach the sensors not exactly at the same time and there may arise consequently some minor deviations. However, the maximum differences amount to only a few degrees and even after five different days there are no long-term differences noticeable. Eventually, 1. 4 shows the solar fraction of a DHW-system according to the collector area and the storage volume (/6/).

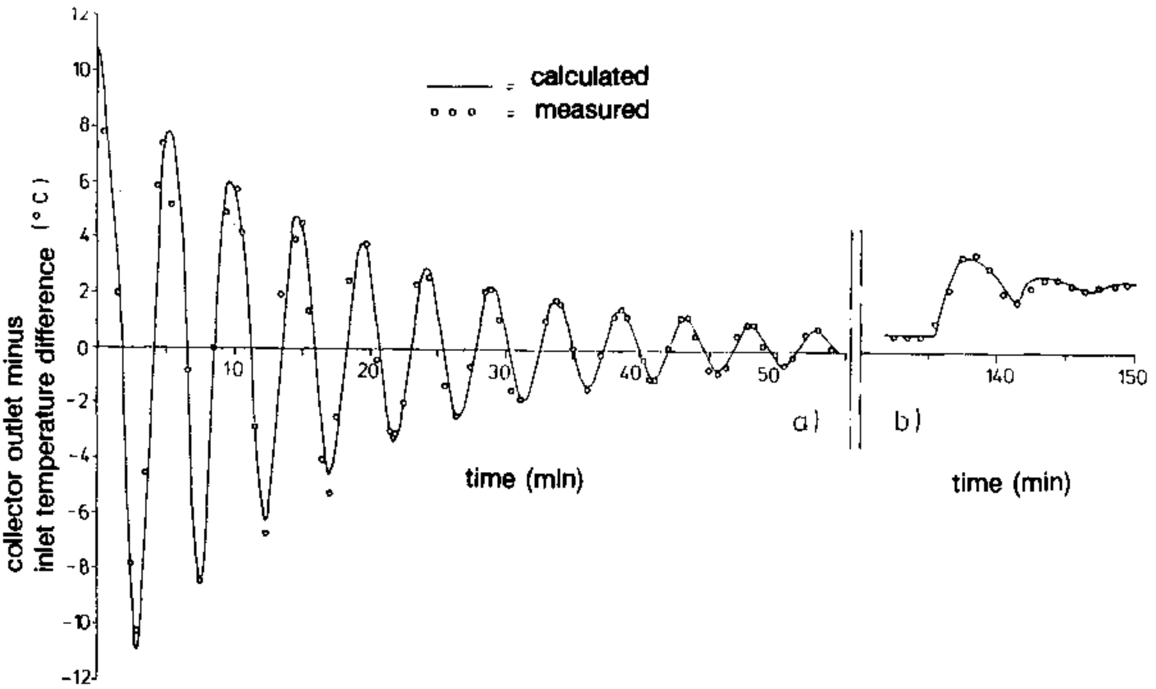


Fig. 1.2 Measured and Calculated Course of the Collector Temperature Difference
a) During Warm-Up Phase
b) after Connection via Heat Exchanger to Load

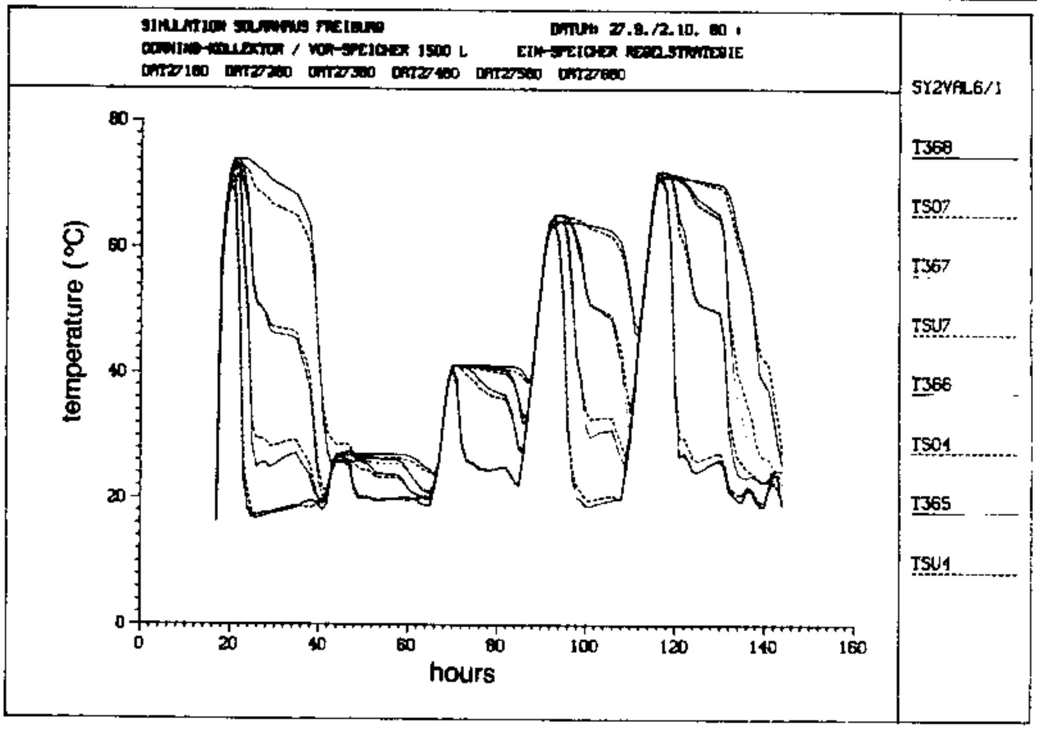


Fig. 1.3 Solarhaus Freiburg: Temperature Course within Preheat Tank (5 Consecutive Days, Measured and Calculated Data)

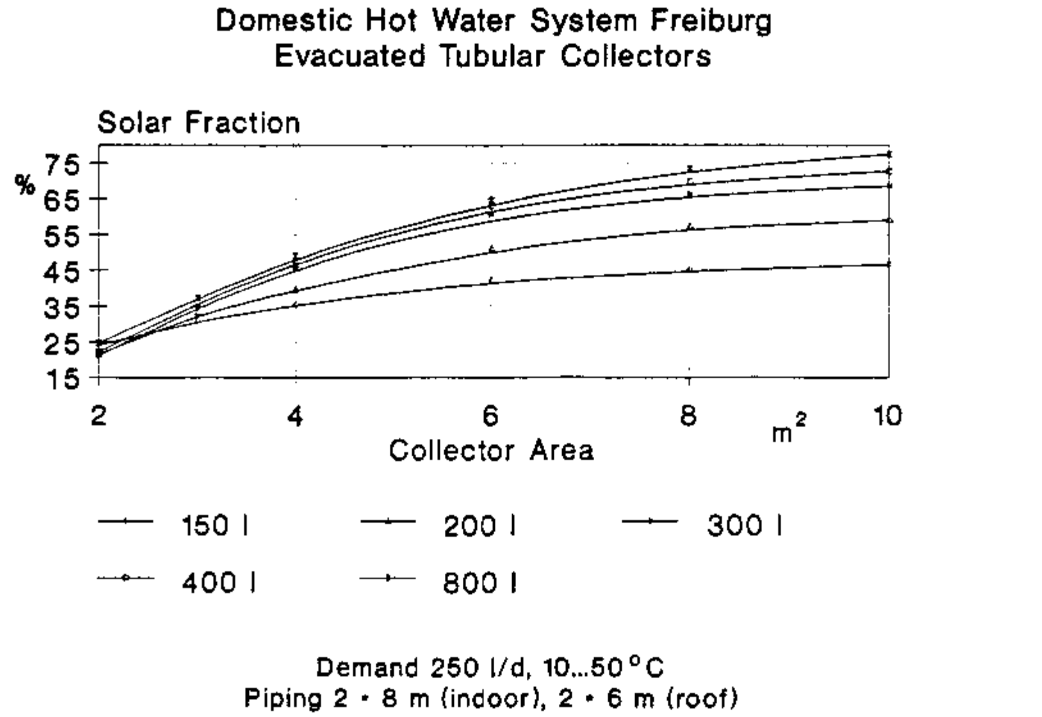


Fig. 1.4 Solar Domestic Hot Water System: Net Solar Fraction Depending on Collector Area and Storage Volume (ISFH-Method)

2. The Origin of System Operational Characteristics

Energy Input /Output Diagrams • Experimental Evidence • Analysis and Investigation • Different Approaches . Relationship to Other Approaches

The generally best known System Operational Characteristics (SOCs) are Input-/Output-Diagrams (IODs). They are a powerful tool for the description of the operational behavior of complex systems and have been used in solar since the late sixties. They were an essential investigative tool of the IEA SH&C Task VI activities, as they are excellently suited for the fast characterization and rating of different systems; however, at least with slight modifications, taking into account various "hidden" parameters, they are not only restricted to the thermal output or to active solar systems only, but are valid for almost all solar energy applications from passive solar houses to large solar tower plants and - in an even more pronounced way - photovoltaic systems. As an example, figs. 2.1...2.5 show the **SOCs (IODs)** for the thermal or electric energy output, respectively, of four different solar thermal installations with operational temperatures up to almost 500 °C, and a photovoltaic one. With these, the daily output is plotted versus the (effective) radiation sum; each point corresponds to one full day of operation. The IODs are either straight lines or only slightly bended. Carefully measured IODs show no more scattering as e. g. outdoor measured collector characteristics, and relate directly to the investigated system: hence it makes surely sense to use those IODs to model the system.

The **origin of these SOCs** has been fully investigated and discussed by the Task VI participants. It will be explained in the next figure. Fig. 2.6 shows schematically the daily radiation profile onto the collector together with some related powers and temperatures. Initially the non-operating collector is preheated to operational temperature (generally some degrees beyond the temperature at the bottom of the tank); the effective thermal loss and capacitance values are those of the collector only. Then the collector pump switches on and the collector and piping temperatures are quickly equalized (the collector temperature drops); the losses and capacitances increase by the respective values of the piping. The collector system is subsequently heated up again either fast by the warm water from the storage tank or - in the case of a bypass (as shown here) - somewhat delayed by the solar radiation. After that, the temperature varies only slowly according to the storage size and the consumer demand. The system shows thus only the (proportional) optical and the (quasi-constant) thermal losses. In the evening, when the useful power output vanishes, the collector pump switches off and the energy stored within the collector system can be only (partially!) recovered in the case of drain-down systems.

Thus the absorbed energy may be split up in

- **the optical losses** of the collector
- **the preheat energy** of the system (depending on the thermal capacity and the storage/ambient temperature difference)

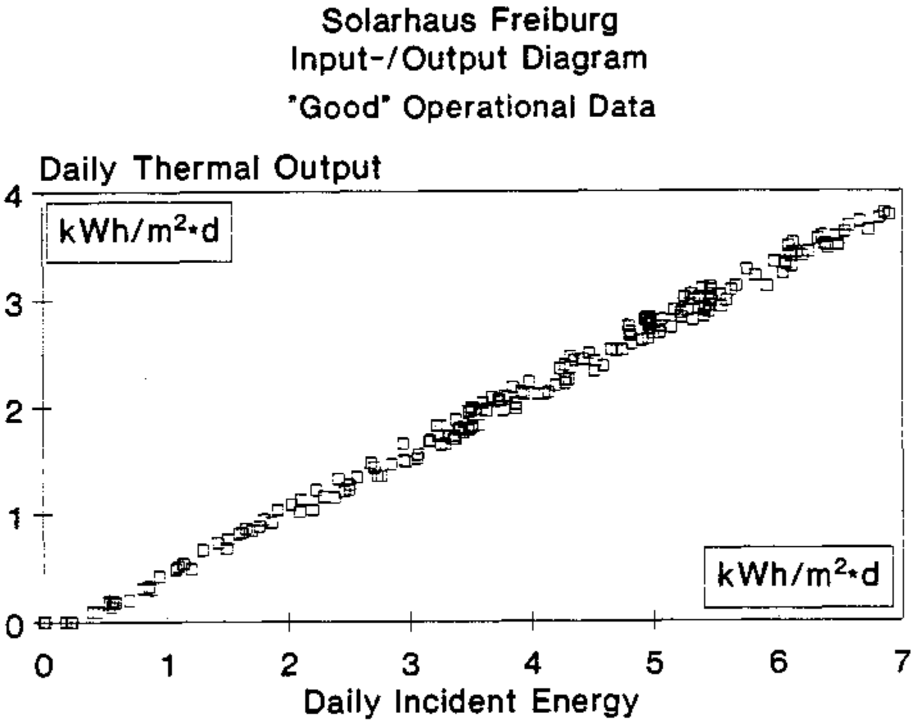


Fig. 2.1 Input-Output Diagramm Solarhaus Freiburg (Corning Collector Field)
Operational Temperature 20...80 °C

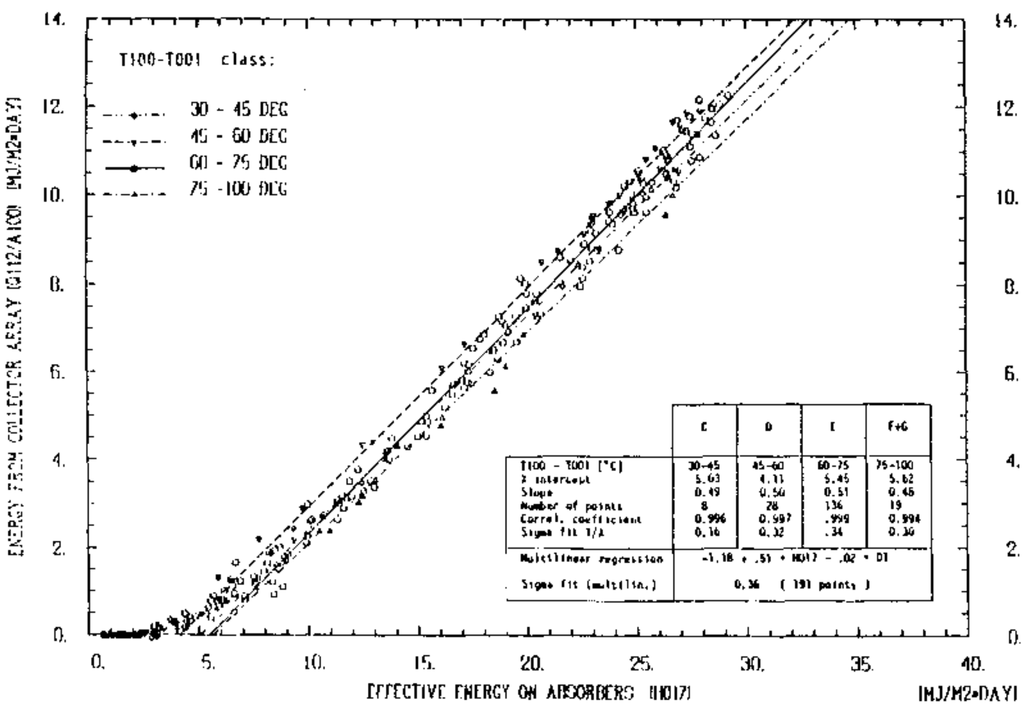


Fig. 2.2 Input-Output Diagram SOLARCAD 1000 (Geneva)
Operational Temperature 50...90 °C

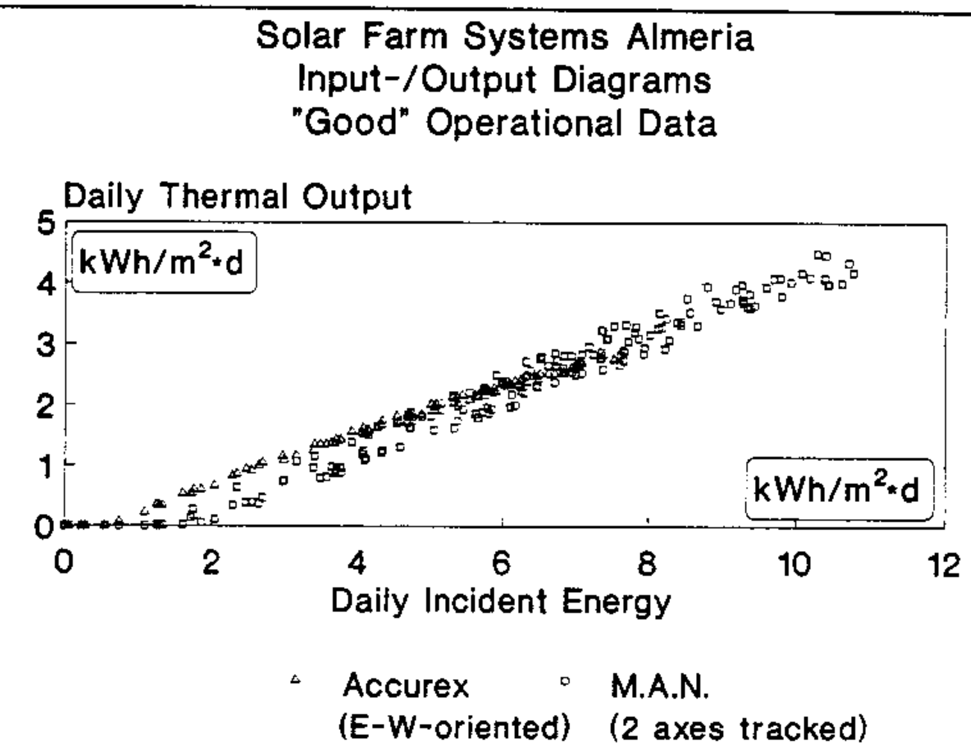


Fig. 2.3 Input-Output Diagrams of the Almeria IEA Solar Farm Systems Operational Temperature 220...290 °C

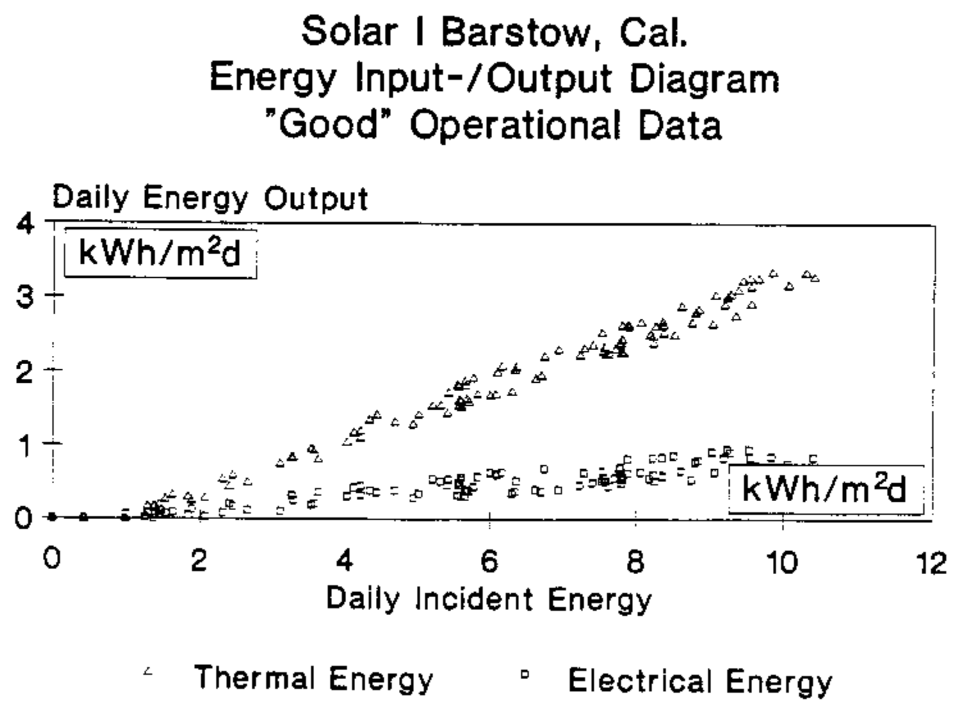


Fig. 2.4 Input/Output Diagram of the 10 MW_e Solar Tower SOLAR I (Barstow) Operational Temperature 450 °C

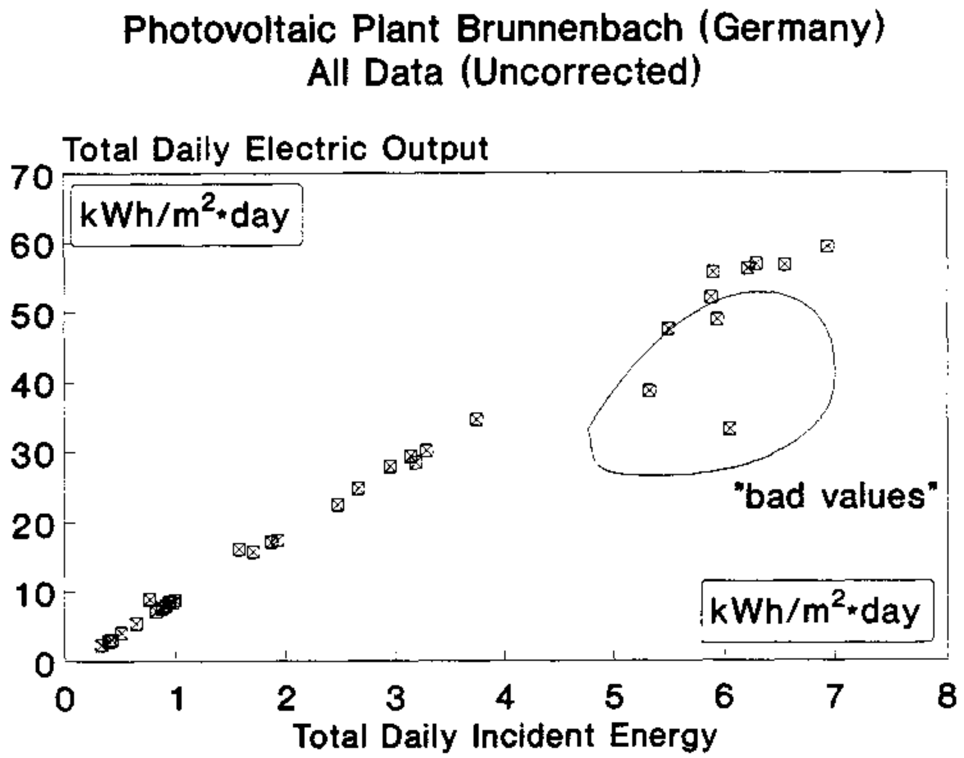


Fig. 2.5 Input-Output Diagram Photovoltaic Installation Brunnenbach

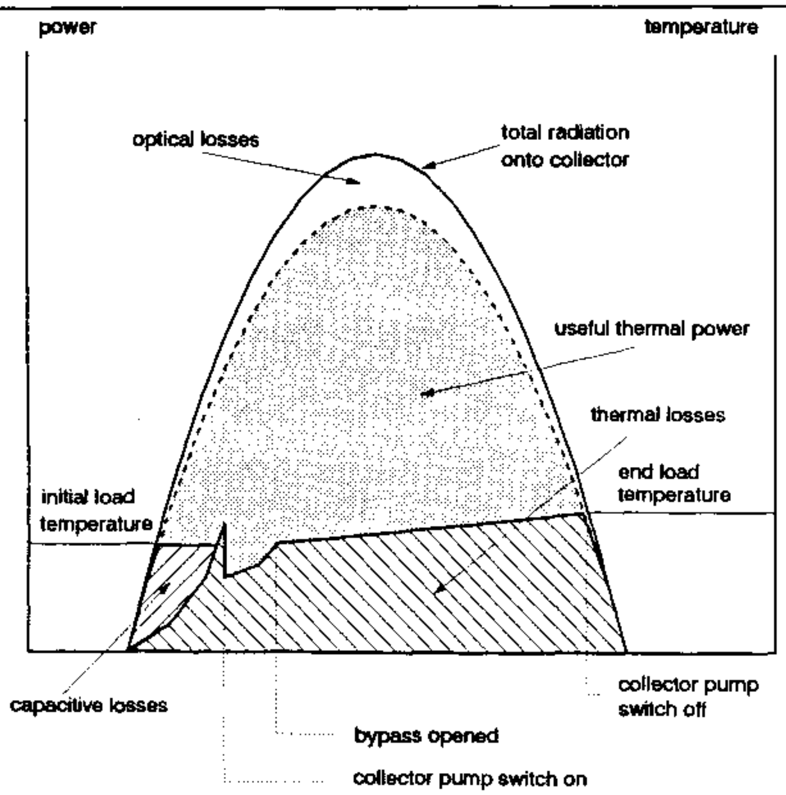


Fig. 2.6 Typical Daily Temperature/Loss Course of a Solar Collector System

- **the thermal losses** during operation (depending on the effective losses of collector and piping, the temperature difference and the operation time)
- **the capacitive losses** after switch-off (which are dissipated afterwards thermally), and
- **the useful energy.**

Hence follows that the **useful energy** output in proper operation is predominantly affected by the **daily radiation sum** and - only secondarily - by the **(mean) temperature difference** and the **operation time** (which on its part is strongly connected to the day length). We expect, therefore, in general linear IODs, somewhat shifted to the right (the capacitive term), and with some operational and seasonal peculiarities. This conforms exactly to the shape of the IODs of figs. 21...2.5.

It follows, furthermore, that **the linearity of a system is closely connected to the losses:** the lower the non-linear losses, the better is the linearity and less hidden parameters have to be taken into account. Hence the derivation of comprehensive SOCs directly from the system parameters (total losses, capacitances, etc.) seems fully justified, if the system is only operated with "favorable" conditions (high insolation, low operational temperature). With "standard" operation conditions, which also cover bad conditions, the detour to component oriented modelling and the subsequent statistical search for "hidden" parameters of influence is surely more appropriate. Which parameters have to be considered ?

Experimentally determined IODs may be easily grouped according to the following parameters

- **incident solar energy H001** onto the collector plane
- **mean operational temperature difference DT** (collector minus ambient
- **operation time TI_{op}**

and are then well suited for the monitoring of an existing plant. Simply by plotting the daily I/O-values, the user gets a good feeling whether his installation is working satisfactorily or not; he may easily detect hidden flaws and - if working carefully - even slowly increasing misadjustments and ageing effects. For design purposes, however, the independent variables

- mean operational temperature difference DT and
- operation time TI_{op}

are extremely unfit, as they are system dependent and consequently unknown. Thus, we have to look for better suited parameters.

A comprehensive investigation (/7/) showed, that a suitable combination of the following parameters provides in almost every case a good description of the thermal output of the collector or the collector system, respectively, with high statistical significance ($r^2 \geq 99$ %):

- **total radiation sum** onto the collector plane H001,
- **mean ambient temperature** T_{amb},
- **reduced day length** DL_r,
- **collector area** A_C, and
- a value describing **the initial state of the storage tank,** which may be given either by the initial mean temperature of the collector connected storage tank T201, or the thermal output Q199 or the total radiation sum of the preceding day H009.

Thus the **output of a single collector** Q112 (no piping, infinite demand, constant inlet temperature) may be represented by

$$Q112 = f(H001, T_{amb}, DL_r)$$

as it is independent of the collector area and the initial state is irrelevant. The **output of a complete collector system** (with piping and storage tank) Q102 is represented by a function

$$Q102 = f(H001, T_{amb}, DL_r, A_c, \{H009, Q199, \text{ or } T201\})$$

whereby either H009, Q199 or T201 describe the influence of the initial conditions on the mean operational temperature (T201, the average initial tank temperature, may be calculated by the respective set of SOCs).

Within this report different system oriented modelling approaches are presented. We group them in

- **"simplified"** ones (e. g. the Swedish and the Swiss approaches), which derive the SOCs directly from comprehensive system parameters and
- **"detailed"** ones (e. g. the German and the US approaches), which perform first numerous calculations on the component level and subsequently statistical regressions to derive the SOCs).

However, **this grouping does not indicate the state of performance** of the different approaches. As to this, only the German and the Swiss model are "complete" ones, i. e. are fully computerized, consistent, ready to use, and are distributed to the public.

Of course, system oriented modelling is not an invention of the Task VI participants. There are earlier examples for both methods. The **"simplified" methods show distinct similarities with some design methods such as the utilizability method** (/8/) or related ones (e. g. /9/). In fact, these approaches are early attempts to expand the range of validity of the Hottel-Whillier-Bliss equation from an instantaneous to a daily basis; however, the differences are nevertheless quite substantial. The system oriented modelling approaches presented in this report originate all from real experiments and consider - at least partially - the impact of all parts of the real system, whereas the above mentioned methods use generally only the characteristics of a single, simply modelled component (the collector) for their approach.

An early example of a "detailed" system oriented modelling approach (i.e. using detailed, component based calculation programmes to derive the SOCs) **is f-chart** (/10/). It has been developed in the early seventies when powerful computers were only available in research laboratories. f-chart was generated by means of numerous TRNSYS calculations (/11/), which were subsequently statistically processed to derive SOCs applicable for a wide range of different systems. Thus f-chart has to consider the whole range of system schematics, operation modes, climates, and consumers. However, due to the extended range of applicability, the corresponding functions are not very specific and the accuracy limited. Nowadays, with powerful and low-cost microcomputers and an appropriate programme available, all these calculations may be performed by the user himself for just the considered system, climate, and consumer. Thus the correlations apply directly to the special system, and the results are far more accurate, dependable, and show far better the outcome of secondary effects.

There may be some more correspondence as to the processing of the climatic data. However, as to our opinion, this should be treated in a sequential rather than a probabilistic way, using either directly TMYs or generating a synthetic climate from long-term averages. Only then the complex interactions within the system may be adequately modelled.

3. Short History of the Task VI Modelling Activities

Importance of Simulation Models • Complex Programs and Simplified Methods . TASK VI Activities

Solar energy systems consist of numerous components such as collectors, piping, heat exchangers, storage tanks, etc.. In order to attain the optimum efficiency and economy, **these components have to be matched mutually and adapted both to the application (the consumer demand) and the climatic conditions.** This matching cannot be achieved by experimental methods only, as the high sensitivity of collector systems against mis-adjustments, the high number of possible parameter variations, the stochastic weather input, and the high expenditure of manpower, time, and costs connected with those experiments prevent a direct comparison. Hence **analytical methods have to be developed,** with which the experimental results may be generalized, the effects of a modified system design investigated, and an extrapolation to other locations and climatic conditions performed. With these methods many **"numerical experiments"** are possible within rather short time and with moderate costs. As even unfavorable designs may be studied easily, the limitations of the respective technology can be readily investigated. Thus the **experiments serve generally as landmarks,** whereas the **modelling and simulation techniques both interpolate in between and extrapolate to new designs, applications, and climates.**

Due to the bearing of simulation models they were thoroughly developed and investigated within the Task VI work. **Modelling work of the participants dates back to the early seventies** and has been steadily improved, compared with other models, and validated experimentally. First rather simple, component based models dominated. In order to save computer memory and time they often used a mixture of simplified analytical and numerical approaches. However, with increasing computer capacity and decreasing costs, they turned more and more to fully numerical methods using main frame computers and taking into account the full complexity of the respective system. Their development and results are described in (/1/).

Beside these complex models the need for simple methods and guidelines for design purposes was always noticed. It can be easily shown, that trend calculations with complex models and their graphical and/or numerical representation by diagrams or tables, respectively, are insufficient to deal with the complexity of real systems. Therefore numerous attempts to develop simple, user friendly calculation models were performed. In the early eighties these were individual approaches and the methods consequently differ considerably in structure, whereas since 1985, after an effort to streamline these activities along the extensively discussed Input-/Output-Diagrams (/12/), they were more correlated. However, each model was developed in close connection both with the Task VI experiments (and some others, too) and with detailed modelling, so that a continuous check and cross-examination with their outcomes was always possible. Thus we are convinced that major errors are avoided and that the results are reliable and trustworthy.

The principal contributors to the area of system based modelling and design tool approaches within the Task VI activities are (in alphabetic order)

- **W. S.** Duff/ E. Boardman (USA) with the investigation of SOCs generated by a detailed component oriented model (TRNSYS) and subsequent statistical processing (chapter 6),

- **W. S.** Duff/ K. den Braven (USA) with the investigation of energy Input-/Output diagrams generated with the basically analytical DAYSIM method,

- B. Lachal/ *O. Guisan* (Switzerland) *with the* ***G³***-Program (chapter *5),*
  This program is commercially available:
  The contact address is
  Prof. O. Guisan
  Université de Geneve, Ecole *de Physique*
  20, rue de l'Ecole-de-Médecine
  CH-1211 Geneve 4
  Switzerland

- E. Mannic (Australia) with a component oriented model to derive the SOCs,

- B. Perers (Sweden) with an experimental/analytical system based design method (chapter 4),

- **G.** Rockendorf (F.R.G.) with an analytical method to generate SOCs (chapter 7),

- K. R. Schreitmüller (F.R.G.) with the ISFH Program (chapter 7),
  This programme is commercially available:
  The contact *address is*
  Dr. M. Mack
  c/o *Institut für Solarenergieforschung*
  Sokelantstr. 5
  3000 *Hannover 1*
  Germany

and

- K. Vanoli (F.R.G.) with a method to generate SOCs with a numerical model and validate them experimentally (chapter 7).

The most interesting approaches are discussed in the following chapters.

4. The Swedish Approach: The Evidence of System Operational Characteristics

1St Stimulus . Experimental IODs • Analytical Expressions • Extensions

The experimentally found pronounced linear relationship of the daily insolation sum and the useful energy output was first analytically investigated by (/13/) at an already very early state. This work was summarized in (/14/).

The main object of this paper is

- **to show and to explain the existence** of these linear connections,
- **to substitute the "unknown" operational values** (operation time, mean operational temperature difference) by the better known values day length and mean daily (i. e. **24** hours) collector-ambient temperature difference, leading thus to a very simple equation system,
- **to derive a method to determine the daily and long-term performance** of both flat plate and evacuated tubular collectors, and
- **to validate this method** by means of several Swedish flat plate and evacuated tubular collector installations.

The authors show that the **daily energy output** fits well the equation

$$Q102 = A*H001 - B*DT(24h) - C \tag{4.1}$$

with

- A the all day zero loss efficiency (i.e. the $\tau\alpha$ -value multiplied by the energy weighted mean of the incidence angle modifiers),
- B the collector array loss factor,
- DT(24 h) the 24 hours average temperature difference between collector mean and ambient,
- C a correction factor allowing for the pumping energy dissipation and the collector and piping capacity.

In most cases, (i.e. well designed installations) C may be neglected and hence the daily efficiency value η_d runs as follows

$$\eta_d = A - \frac{B \cdot DT(24h)}{H001} \tag{4.2}$$

which is well proven by the experimental results (fig. 4.1).

This means, that the all day collector performance may be derived directly from some easily measured 24 hours data, which are essentially independent of the system design, irradiation pattern, etc. (the secondary influence of the insolation sum on the above mentioned parameters is nevertheless discussed).

Subsequently it is shown, that for the investigated Swedish installations quite linear relationships exist

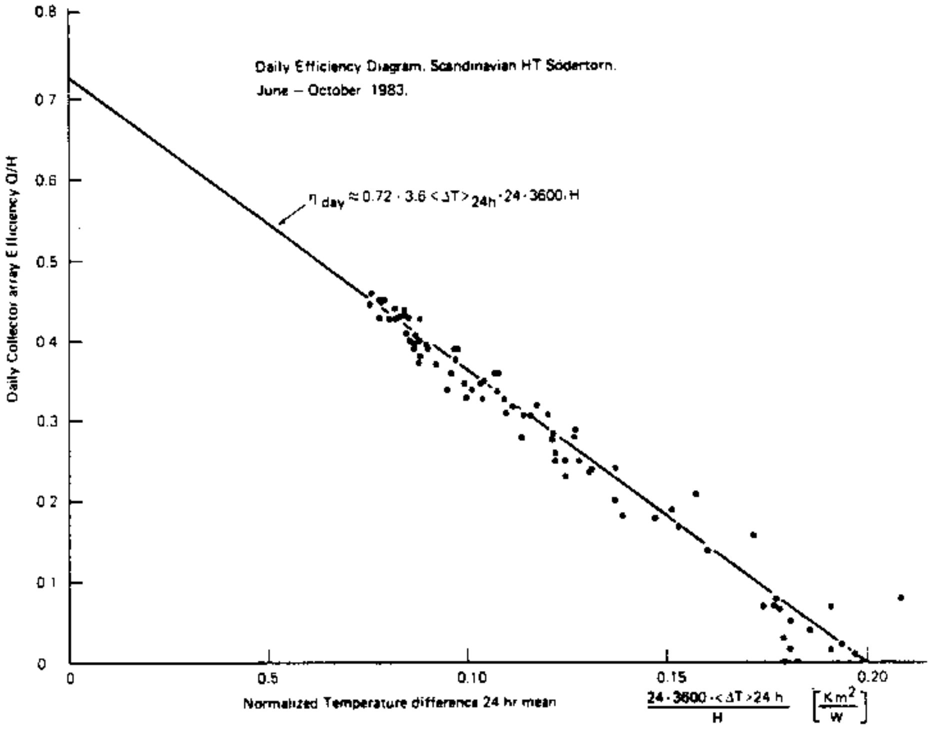


Fig. 4.1 Daily Efficiency Diagram for Scandinavian HT Södertörn (District Heating System)

- for the daily collector insolation sum H001 and the period with radiation densities exceeding a certain threshold value (i.e. 200 W/m^2)
- for the daily collector insolation sum H001 and the length of the operation period,
- and for the monthly average day length and mean daily insolation sum.

These connections have been used to derive **analytical expressions for the monthly average performance of different collector installations operated essentially with constant temperature difference;** the **agreement with the experimental data is surprisingly good** for this straightforward approach.

The authors come to the following conclusions:

- **there exist simple expressions for the daily collector output** of the form

$$Q102 = A \cdot H001 - B \cdot DT(24h) - C$$

- **the characteristics are dependent both on climate and season,**
- **the dependence may be accurately taken into account** by means of the average difference between collector mean and ambient temperature,
- **a certain scattering of the daily I/O-values is due to secondary effects as e.g.** the insolation pattern; the scatter is more pronounced with high collector losses, operational temperatures, etc. (i.e. "unfavorable" conditions)
- **the daily characteristics may be extended to monthly and annual characteristics.**

5. The Swiss Approach: The Application of System Operational Characteristics

Analytical Model • Range of Application • Diagrams • Computer Program: Extensions

During the Task VI activities and, especially, within the concerted action to develop I/O-based design tools, various analytical, thus simplified (non-numerical) approaches to determine IODs and the output of collector systems have been performed by the participants (/15, 16, 17, 18/). However, the **most uncompromising attempt for a non-computerized method is the G^3-Model** (/19/). With this, the authors laid particular emphasis on the fact, that by the use of precomputed diagrams and tables hand made evaluations are possible without any computer. However, recently this method was **transferred to the computer level and substantially extended** (called now **G^3-Program,** /20, 21, **22, 23/).** It is commercially available (→ chapter 3) and participated in the modelling workshop (→ chapter 8).

The original method consists principally in the **investigation of the temperature course of a simply modelled collector system** (one node, either taking into account only the collector losses/capacity [non-operational case] or those of the piping, too [operational case]). Thus the system is reduced on one single linear differential equation, which is solved analytically. In order to perform easily analytical integrations the model uses some simplified assumptions such as

- daily radiation profile sinusoidal,
- pump contributions negligible,
- load as well as ambient temperature constant during the day,
- collector subsystem (i. e. including piping) always isothermal (i. e. load temperature in operational case),
- incidence angle modifiers constant (included in the optical efficiency),
- collector orientation close to south (with arbitrary inclination).

Thus this method is especially aimed at **installations with high and constant demand, high specific mass flow rate** (collector subsystem isothermal) and working at a **nearly constant, elevated temperature** (load to ambient temperature difference constant throughout the day); good examples of those systems are **district heating or industrial process heating systems.**

The collector system is characterized by three parameters, i.e.

- **the collector optical efficiency** (called ETA),
- **the total heat loss factor** (called K) of the collection subsystem (with/without piping), and
- **the total thermal capacity (C),**

all being normalized to the aperture area. The **load** is characterized by an **infinite demand and a constant temperature difference** DT between collector and ambient. With the day length DL and the daily radiation sum H001 (onto the collector plane) the problem is reduced to the following six parameters

$$Q102 = f(ETA, K, C, DT, H001, DL),$$

with the first three ones referring to the collector system, the fourth to the load, and the last two ones to the solar radiation.

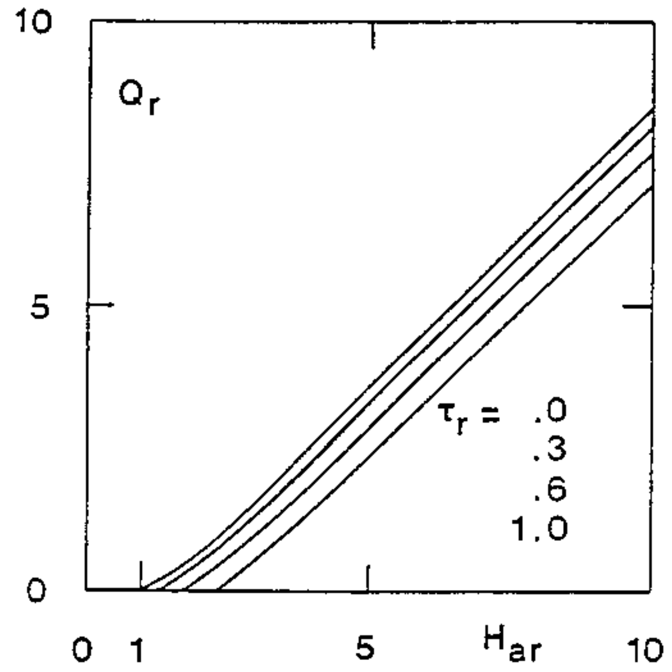


Fig. 5.1 G^3-Model: "Universal I/O-Diagram"

With some intermediate calculations dimensionless values of the system parameters (indicated by the index "r") are derived in order to generate **"universal daily I/O diagrams for any system, under any condition, with an accuracy similar to that of detailed simulations".** Essentially two diagrams are given showing the connections

$$Q_r = Q_r(H_{ar}, \tau_r)$$

and

$$OT_r = OT_r(H_{ar}, \tau_r)$$

thus connecting the thermal output O_r and the operation time OT_r, respectively, with the insolation sum H_{ar} (reduced values each). An example is shown in fig. 5.1 and fig. 5.2. By means of the (seasonally varying) reduced time constant τ the daily data may be plotted into these diagrams. The authors compare for validation purposes the measured values of a Swiss district heat installation which correspond well to the G^3-curves (fig. 5.3).

Recently the G^3-model was computerized (now called "G^3-Program") and most limitations of the analytical model have been omitted. Thus the programme is closer to reality. The method includes now

- **the temperature dependency of the losses** of the collector subsystem,
- **an average temperature drop between collection subsystem and load** which approximates heat exchanger effects and piping losses,
- **varying storage tank temperatures** approximated by an average daily value (obtained by iterations),
- **a new solar radiation generator** based on the Liu-Jordan correlation,
- **incidence angle modifiers** and
- **shading effects.**

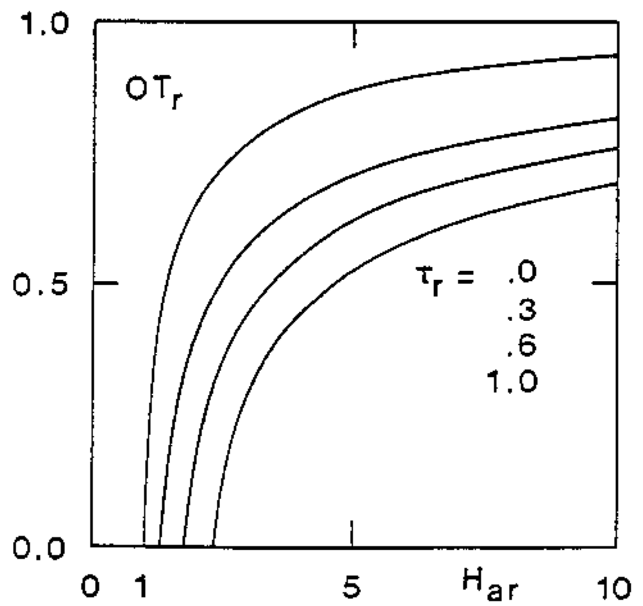


Fig. 5.2 G^3-Model: Diagram for the Determination of the Operation Time

The G^3-Program covers **collector systems without storage (i.** e. district heating systems) or with **one or two storage tanks (i.** e. DHW/IPH systems). With IPH systems several control strategies and/or operation modes (priority to load, reduced load on weekends, etc.) are possible.

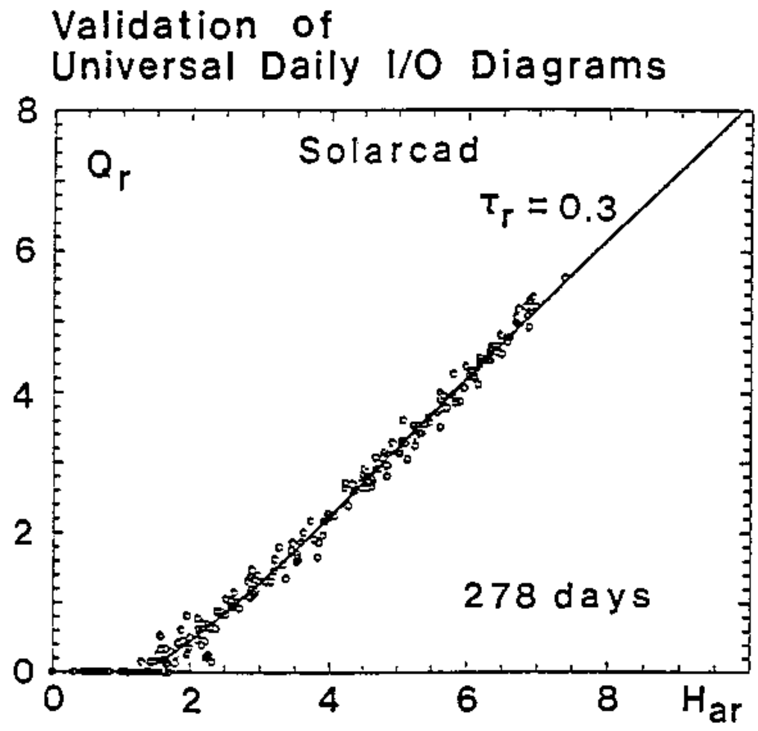


Fig. 5.3 G^3-Curves Compared with Experimental Data (District Heating System)

6. The US Approach: The Validation of System Oriented Simulation Models

TRNSYS Calculations • Statistical Processing and Investigation . "Local" and "Multi-Climate" Model . Accuracy . Conclusions

The investigation of the structure of energy Input-/Output-Diagrams and their applicability for design purposes was one of the focal points during the IEA Task VI work. In the beginning the existence and the origin of these characteristics were thoroughly discussed; however, with the growing understanding of the related their applicability as design tools and their validation attracted increasing attention. Various external reports and internal communications dealt with this subject. However, the statistically most convincing and likewise comprehensive investigations were performed by (/24, 25/). Hence we restrict ourselves within our report on this paper.

The structure of the work is shortly the following

- 1 **determination of the operational behavior** of solar DHW and IPH systems for one or several cities by means of TRNSYS and hourly meteorological values (TMYs),
- **2** **statistical processing** of the daily collector output in order to derive a set of SOCs for both types of installations,
- **3** **validation of this procedure** by determining the daily/monthly/annual collector output for different cities both with the original TRNSYS model and the generated SOCs and comparing the respective results.

This approach is principally similar to that of the ISFH-model (chapter 7), with the main difference, that the different parts - whether of own or foreign origin - are not combined into one consistent model. It is therefore rather a **"performance extrapolation method",** with which **manufacturers may determine the output of a fixed installation** with various climatic conditions than a method to design and to investigate a completely new installation. However, within the context of the Task VI work on system modelling, its main value is **to provide extensive information on the achievable accuracy and the statistical background and justification of these approaches.** In the following the procedure is explained.

Two generic types of systems have been examined. These were various **IPH systems** (ETC, A_c = 250...1000 m^2, infinite demand, inlet temperature 40...110 °C) and one **DHW system** (daily demand 300 l, FPC, A_c = 6.5 m^2, heat exchanger efficiency 90 %, storage volume 454 l), which have been modelled with Toronto weather data. The ETC was a high performance heatpipe collector with temperature-dependent losses, whereas the FPC was a standard flat plate collector with a constant thermal loss value. Thus a rather wide variation of collector constructions is considered. **Various radiation processors** are applied to determine the insolation onto the inclined collector plane. The differences of the radiation models are demonstrated and compared with experimental data.

The results were then statistically processed to generate a **"local SOC model"** (i. e. for Toronto). Different regression methods were applied. The daily insolation sum onto the collector plane **H001** proved always to be the primary parameter of influence, alone accounting for a regression coefficient r^2 = 95...96 %. From the Task VI experiments the mean operational temperature difference **DT** and the length of the operation time $\mathbf{TI_{op}}$ were identified as parameters of secondary importance. In order to change easily the location, the "unknown" parameter TI was replaced by the day length DL. For the IPH system the next most important variable was then $\mathbf{DL*DT^2}$, which, together with H001, provided a r^2 = 99.5 %. Additional variables appear in the order of $\mathbf{H001^2}$, **DL*DT*H001** and **DT*DL.** The complete model takes into account the influence of the collector area as well (which is especially important in combination with an extended piping) and consists of up to seven parameters, i.e.

$$Q112 = A_0 + A_1 \cdot H001 + A_2 \cdot H001^2 + A_3 \cdot A_c + A_4 \cdot A_c^2 + A_5 \cdot DT + A_6 \cdot DL \cdot DT + A_7 \cdot DL \cdot DT^2 + A_8 \cdot H001 \cdot DL \cdot DT \quad (6.1)$$

For the **DHW case,** $\mathbf{DL*DT^2}$ proved to be insignificant (this may be due to the constant, i. e. temperature independent thermal loss value of the collector model). As the collector area is constant, the number of parameters is reduced to four.

The initial TRNSYS calculations were subsequently repeated for other locations (Albuquerque, Miami, Seattle) and the results used to generate a **"multi-climate performance model".** Eventually the resulting two SOC models were validated against TRNSYS with new climatic data. The **solar fraction rates on a daily basis showed excellent agreement.** We quote here only the results of the IPH systems, as there are more system modifications and, therefore, a broader survey is possible. The relative **errors of the "local performance model" amount to approximately 1...2** %, those of the **"multi-climate model" are generally below 1** %. Even more impressive is the agreement on a daily basis. The typical error bands, in which 90 % of all results fall, amount to ± 2 % (Miami), ± 3.5 % (Albuquerque) and ± 5 % (Seattle).

Similar investigations have been performed with the output of the collector system 0102. Although the relative errors increase (typically by a factor of two), the overall accuracy is quite satisfactorily and allows an **easy and fast determination of the system's performance on a daily, monthly, and annual basis.**

The authors conclude that, although the generation of these performance models requires a host of either experimentally or numerically gained results, **the models themselves are extremely easy to use and very accurate,** even on a daily basis. They have shown that the derived **SOCs are valid for a large range of operational conditions, for greatly differing climates, and for "reasonable" extrapolations.**

They have proven that the prediction capabilities of the performance models are very close to that of the detailed simulation model (TRNSYS) and that virtually **no additional errors emerge from their application;** thus, **if improved accuracy is really needed, it may be more desirable to improve some modules of the detailed model (e.g.** collector and/or storage model, radiation processor, etc.) in order to reduce the related errors. **The subsequent mathematical condensation to SOCs, if properly done, produces only marginal errors.**

7. The German Approaches: Background, Determination and Application of System Oriented Simulation Models

Survey • Characteristics of Respective Components • Determination of System Characteristics • Application of System Characteristics . Monthly/ Daily Meteo Data • Synthetic Climate • Radiation Processors • Incidence Angle Modifiers . Tracking Collectors . Shading . Validation . Examples

7.1 Survey

Within the Federal Republic of Germany three methods have been developed in the context of the IEA Task VI activities on user friendly design methods, i. e.

- 1 **an approach to solve analytically the respective set of differential equations** in closed form in order to derive the energy IOD's of a collector system (/26/),
- **2 an approach to derive numerically energy IOD's of a solar installation** and to compare it with experimental ones (/27/),
- 3 **a method to determine and to apply these SOCs** by
  detailed calculations on the subcomponent/component level and subsequent statistical processing,
  to determine the thermal output, and - if applicable - the solar fraction, maximum temperatures, and the surplus energy of a given collector system (/28, 29/).

This last method is commercially available (→ chapter 3) and participated in the modelling workshop (→ chapter 8).

The development of all three methods was closely coordinated and the results have been extensively compared. The first approach is comparable to the G ^{3}-Model, as it **solves the respective set of differential equations with classical analytical methods.** It demonstrates that this approach is quite possible with simplified assumptions (e.g. a well mixed storage tank, one forward/return piping, collector losses independent of operation temperature). However, the time saving is rather insignificant, especially as the control functions (on/off of the collector pump) need some lengthy iterations. But the main disadvantage of this approach is its inherent inflexibility, as each new component requires substantial new mathematical work. The result was of course anticipated and the work served primarily to verify this assumption.

The second approach was performed in order **to compare numerically derived energy IODs with those measured at the "Solarhaus Freiburg" installation.** It has been shown that the experimentally determined energy IODs based on day length, total radiation sum onto collector plane and mean operational temperature difference (collector minus ambient) correspond well to the numerical ones and that a similar modelling approach is fully justified. Furthermore a simple computerized design method has been developed within this work.

The third approach is by far the most complete calculation method within the IEA Task VI context. It shall be treated, therefore, in greater detail. It is based on various component based simulation programmes (e. g. /30, 31, 32/) and extensive experimental work (/33, 34, 35, 36, 37/).

The philosophy **of** the method **is**

a) **the determination of comprehensive characteristics** (of components as well as of systems) by means of detailed modelling on the respective "lower level" and subsequent statistical processing and

b) **the application of these characteristics** in the next level.

Hence the component characteristics are determined - if not otherwise available - by careful modelling on the subcomponent level, the system's performance on the level of components. Thus this procedure concentrates first on the essential parts of the system, i. e. the description of complex interactive connections, whereas the routine hour-by-hour, day-by-day calculations are performed on the level of SOCs.

The structure of the method is shown in Table 7.1. It consists of two main parts, with the first determining the SOCs of a given installation (with variations) and the second one using these to calculate the monthly and annual performance of the installation. Within both parts, **modifications may be performed in order to extend the range of application.** The code is **virtually self-explaining,** that is, it is fully supplied with "help files" to provide explanations if needed. Some subprogrammes are provided or planned for particular information (i.e. **piping optimization, collector characteristics, incident angle modifiers,** etc.). The program runs on 286-PCs and upgraded computers.

7.2 The Determination of the System Characteristics (IODs)

The following "systems" may be investigated

insolation onto an arbitrarily oriented, if needed, tracked plane (four different tracking modes possible, without or with incidence angle modifiers)

collector only, with constant or seasonally variable inlet temperature and unlimited demand (very fast calculation, but rather academic and only suited for fast comparisons)

collector with piping, heat exchanger, constant/variable inlet temperature and unlimited demand (e.g. large district heating systems or industrial process heat systems without storage)

collector with piping, heat exchanger, and (one or. two) storage tank(s) (domestic hot water/industrial process heat system with limited demand).

The COLLECTOR is the most important component of the system. It is modelled in a detailed manner. The collector model, shown in Fi. 7.1, is basically a physical one. The following parameters are taken into account

Table 7.1 Structure of the ISFH Simulation Model

1. Definitions "Ideal System"

COMPONENT	DATA BANK	SUB PROGRAMMES
Storage Tank(s) (none/one/two tanks)	6 Heat Transfer Fluids	
Collector	10 Generic Types	Determination of Characteristics according to Design & Operational Conditions
Controls	3 Different Control Strategies	
Piping	6 Heat Transfer Fluids	(Optimization)
Heat Exchanger		Internal HX (Characteristics according to Design and Operational Conditions)
Consumer (Temperature & Total Demand, Daily/Weekly Profile)		
Weather Data	3 Generic Types	

Determination of System Operational Characteristics (SOCs)

2. Definition "Real System"

VALUE/EFFECT	DATA BANK/ RESULTS	SUB PROGRAMMES
Climate	>350 Cities + >30 TMYs	5 Radiation Processors + User's Data
Collector System	(Area & Orientation)	
Optical Parameters	11 Standard Values	Refraction Index & No. of Panes or User's Data (Orthogonal IAMs)
Shading		User's Data
Tracking Systems	Fixed & 4 Tracking Methods	

3. Results

Collector Output
Solar Fraction
Surplus Energy

- **optical efficiency:** The optical efficiency τα a with normal (i.e. vertical) incidence is modelled as being independent of the radiation intensity (as in reality; the apparent τ α-dependence of some collectors is due to the limited absorber-fluid conductivity); the variations of the optical acceptance with inclined radiation (incidence

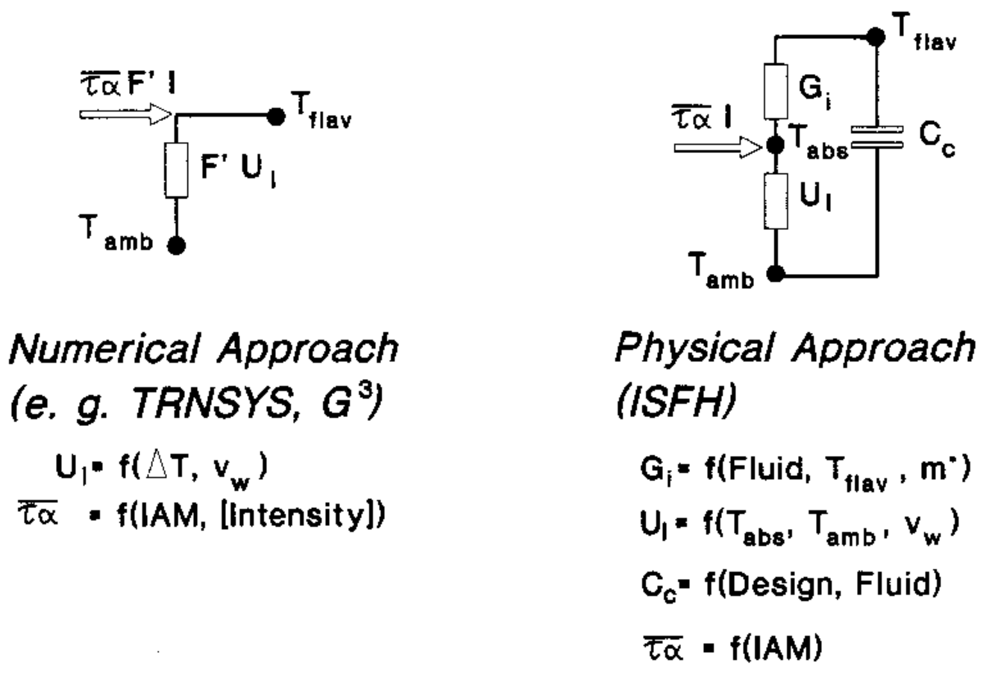


Fig. 7.1 Standard and ISFH Collector Model

angle modifiers) are taken into account within part B by means of orthogonal functions and either symmetric or asymmetric acceptance angles,

- **internal absorber-fluid conductivity:** This parameter is especially important with heatpipe collectors, **as** it may then be rather limited and the mean absorber temperature consequently higher than the mean fluid temperature; it is assumed to be slightly dependent on the total flow rate (fig. 7.2: important with microflow operation),

- **thermal losses:** the thermal loss value is described by the equation

$$U_c = (U_0 + U_1 \cdot T_{ABS} + U_2 \cdot T_{amb}) \cdot (1 + v_w \cdot C_w) \qquad (7.1)$$

  thus depending on (mean) absorber temperature, ambient temperature, and wind velocity (this approach is superior to the conventional U_0 + U1*ΔT especially with variable climatic conditions); the thermal losses are assumed to increase linearly with wind velocity, with the proportional factor C_w being a specific constant for each collector (fig. 7.3); reference temperature is the mean absorber temperature (this approach is valid down to very low specific flow rates)

- **thermal capacitance:** This parameter depends on the collector construction and the type of the heat transfer medium; it is assumed to be constant (the tempera

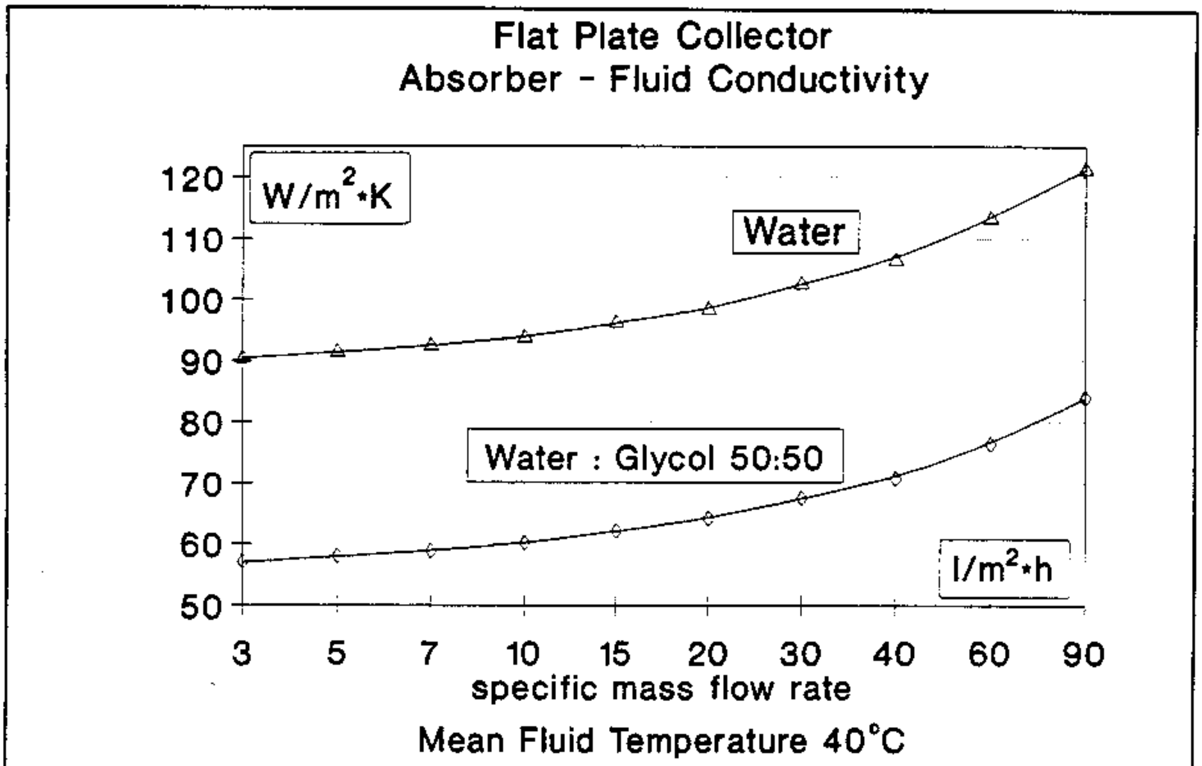


Fig. 7.2 Internal Conductivity Depending on the Properties of Heat Transfer Fluid and Specific Mass Flow Rate (SFPC, Example)

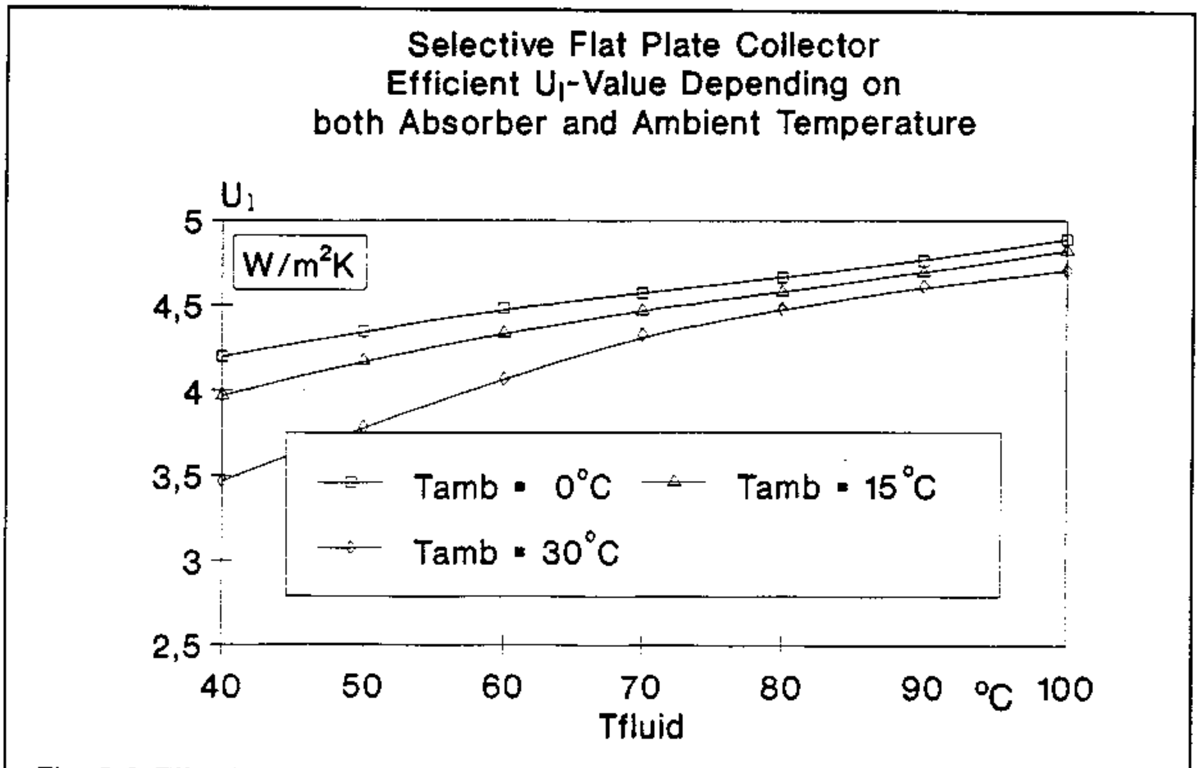


Fig. 7.3 Effective U_l-Value of Selective Flat Plate Collector Depending on Mean Absorber and Ambient Temperature (Example)

ture dependence of the fluid capacitance is not accounted for), and the reference temperature is the mean fluid temperature.

This model proved to be substantially superior to the standard approach with quadratic losses only when compared with detailed measurements and simulations. However it uses some uncommon parameters (thermal loss parameters, internal conductivity, incidence angle modifiers). In order to avoid frustration for newcomers those values are given for a wide range of collector constructions, but they may be determined equally by means of special subprogrammes for a given collector construction, or a regression fit is performed with measured data.

Three different CONTROL STRATEGIES are possible

- mass flow rate is constant, or
- mass flow rate variable, with the collector output temperature equal to the set temperature, or
- mass flow rate variable, with the collector output temperature equal to the temperature of the storage layer where the return flow enters the tank plus an optional temperature difference.

The "Collector On" and "Collector Off" temperature differences are optional.

The STORAGE TANK is the next most important component. One or two serially connected tanks are possible. They are each described by the following parameters

- the total volume,
- the effective conductance of the insulation material (which may exceed the calculatory one substantially due to thermal bridges, break-throughs, insulation flaws, etc.),
- the insulation thickness,
- the number of layers within the tank (up to 99 layers possible),
- the number of (upper) heated layers,
- the aspect ratio (height/diameter),
- the ambient temperature (either indoor and constant or outdoor and varying),
- the existence of a bypass,
- the return layer (return flow from collector or heat exchanger, resp.),
- the maximum tank temperature.

The thermal losses are distributed on the different storage layers according to their respective surface area, thus are concentrated in the lower and upper part of the tank. The interaction between adjacent layers is due to

- volume flow (collector/heat exchanger flow <u>and</u> demand flow),
- conduction (only due to the storage medium, not to the tank shell),
- convection.

A "partial" mixing of the collector/heat exchanger return flow with the respective return layer is assumed if its temperature is below that of this layer; in the other case, the mixing is complete.

INTERNAL and EXTERNAL HEAT EXCHANGERS are possible. **External heat exchangers** are characterized by three parameters, i.e.
- the specific exchanger value (W/K),
- the storage layer of the return flow,
- the capacitance flow ratio (primary to secondary flow).

The **characterization of internal heat exchangers is far more complex.** It is per formed in the following manner
- the heat exchanger is within the lowest (coldest) storage layer,
- the heat exchanger coil is described by its geometrical dimensions and the con ductivity of the material,
- the internal (collector fluid) and secondary (storage medium) Reynolds and Prandtl numbers are determined according to the material properties of the respective fluids and the relevant temperatures according to (/38/) for approximately 80 different operational conditions,
- the Nusselt numbers and the effective heat exchanger values are determined according to the operational conditions and subsequently statistically processed to derive the respective HX characteristic.

For given design, mass flow rate, and material properties the exchange factor UHX is depending both on inlet and storage temperature according to the formula

$$U_{HX} = U_0 + U_1 \cdot T_1 + U_2 \cdot T_2 + U_3 \cdot T_1^2 + U_4 \cdot T_2^2 + U_5 \cdot T_1 \cdot T_2 \qquad (7.2)$$

(T_1 fluid inlet temperature, T_2 temperature of respective layer of storage tank). The exchange factor of an internal heat exchanger depending on the operational conditions is shown in fig. 7.4.

The FORWARD and RETURN PIPING may each consist of different serially connected parts (e.g. the piping of a large collector field with twelve collector loops may consist of two parts: a single forward/return pipe to the field and twelve parallel pipes within the loops). Each part is characterized by six values, i.e.
- the length of the respective pipe (with several pipes in parallel: average pipe length),
- the inner diameter of the pipe,
- the effective conductance of the insulation (W/m*K), taking into account all thermal bridges, leakages and flaws of the insulation; this value may consequently exceed that of the material itself substantially,
- the ambient temperature (either indoor and constant or outdoor and varying),
- the number of parallel pipes of the same kind.

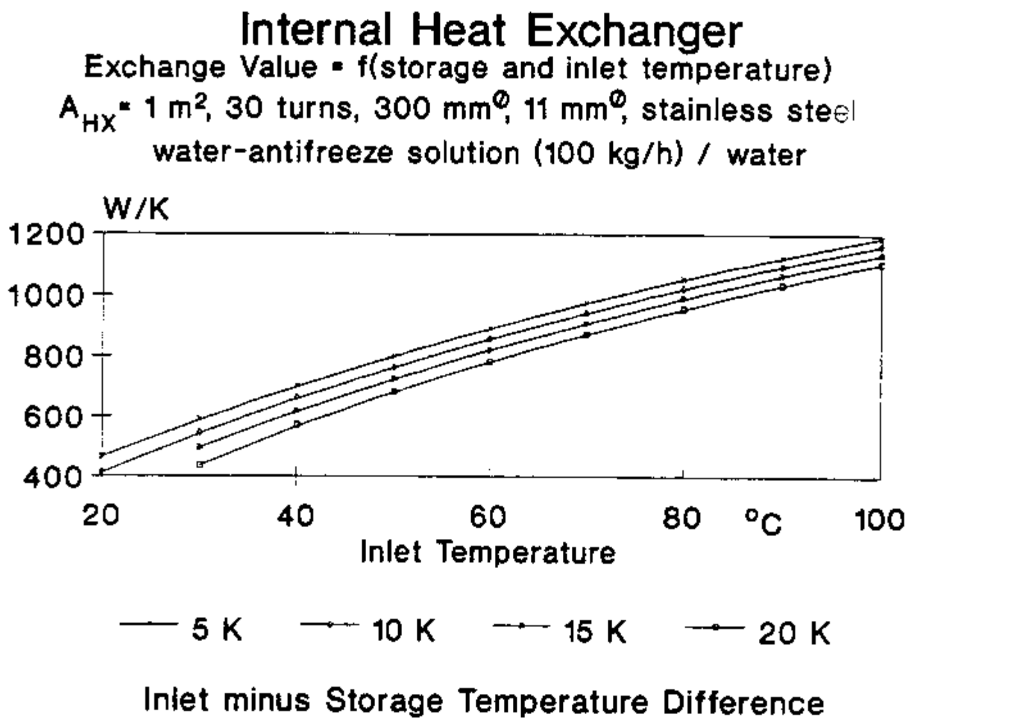


Fig. 7.4 Characteristic Exchange Factor of an Internal Heat Exchanger Depending on the Operational Conditions (Example)

The wall thickness of the tubes and thus the capacity of the (empty) tubes is determined according to a German standard for steel tubes (DIN **2449).** Other standards for both steel and copper tubes will be shortly implemented.

This description illustrates that ISFH models the respective components - especially the collector and the internal heat exchanger - in a far more detailed way as other simulation programmes, e. g. TRNSYS.

The CONSUMER is characterized by the following parameters:
- the total daily/weekly hot water demand,
- the demand temperature,
- the (cold) water inlet temperature (either from mains or return flow from process), which may show a seasonal swing (e. g. the return temperature of a district heating system, which is higher in winter),
- the demand profile, which may be defined in hourly steps.

There is a recommendation for the **TIMESTEP,** which provides a "reasonable" accuracy. For very accurate calculations it may be decreased by a factor of two to three.

After these definitions determines the program the behavior of the system
- for two different day lengths (9 and 15 hrs.)

- for two different mean ambient temperatures (given mean ambient temperature ± 10 °C)
- for two different collector areas (minimum and maximum),
- and a set of eight (fifteen) subsequent days with varying insolation,

thus for a sample of up to 120 days. **All differential equations are solved simultaneously;** if two circuits of a system are coupled indirectly via a heat exchanger or similar, then the respective temperature levels are determined by iteration. The daily results are either plotted graphically or printed numerically on the screen; a hardcopy is also possible.

When all daily values are determined the statistical processing takes place. Here a comment as to the optimal choice of the independent parameters is necessary. We identified up to nine, partially composed parameters of influence to describe the output of the collector system and the solar fraction, which lead typically to regression coefficients $r^2 \geq$ 99.5 %. Thus we are quite confident, that this mathematical compression does not imply major errors. However, for some other parameters of interest (i. e. maximum tank temperature, surplus energy, and else) the regression coefficients are significantly lower (96...98 %), and we look further for better approaches.

All **relevant values of the system may be stored** for later use. The regression parameters (now called "system operational characteristics", SOCs) are used within part B for the determination of the system's output.

After these calculations, which need typically a few minutes on a 386-PC, **modifications** may be performed, in order to obtain the set of system parameters for different components or system schematics.

7.3 The Application of the System Operational Characteristics to Design an Active Solar Energy System

The envisaged application area of the ISFH-model includes developing countries, too, where TMYs are hardly available. Thus monthly averages of the daily radiation sum and the mean ambient temperature are used to generate a **"synthetic climate"** consisting of some good, average, and bad days (the number of days depends on the weather variability of the respective location). The monthly averages are available within a subprogramme for more than 350 locations all over the world. However, the user may implement his own climatic values as well. The mean monthly and daily values of more than 30 US TMYs are similarly implemented (when daily values are used the implications connected to the synthetical climate are of course excluded).

The "real" system is then characterized by the following parameters:

- **the relevant set of system parameters** (from part A),
- **the daily demand** (similarly as in part A),
- **the collector area and orientation** (inclination and azimuth),

- **the incident angle modifiers** (either symmetric or asymmetric),
- **the acceptance angles** (either symmetric or asymmetric),
- **the tracking system** (either fixed mounting or four different tracking modes possible),
- **the possible obstructions** shading the collector,
- **the respective storage values** (overall loss value, ambient and maximum temperature).

The parameters should, if applicable, correspond to or be at least similar to those used within part A. Thus a set of regression coefficients derived for collector areas $A_c = 3...7\ m^2$ may be used for an area of $8\ m^2$, too, but must not used for $40\ m^2$. For these cases with extended parameter variations several calculations within part A have to be performed and the respective sets of regression coefficients chosen.

The calculation includes the following steps
- generation of the synthetical climate
- determination of the daily radiation sums onto the collector plane
- determination of the thermal output and - if applicable - the solar fraction by means of the SOCs.

The determination of the instantaneous beam and diffuse radiation densities is done in the following way (this applies if monthly means are used; the development of a synthetical climate using daily means is of course far simpler)
- the daily radiation sum on the horizontal plane is calculated for "good", "average", and "bad" days basing on the monthly means,
- the daily diffuse to total radiation ratio is determined using a correlation similar to (/39, 40/); however, it shows a dependency to the mean monthly solar altitude (i.e., the daily diffuse to total radiation ratios are higher with low solar altitudes (/41/); other radiation processors are similarly available,
- the instantaneous diffuse to total radiation ratio is determined taking into account the respective air mass; the extraterrestrial radiation density is chosen in order to fit both the daily radiation sum and the diffuse to total radiation ratio. This approach corresponds to a two-fold extinction model, where one part of the spectrum is absorbed completely and the remainder only partially within the atmosphere.

When using daily values the implications connected to the synthetical climate are avoided. The radiation densities are then chosen to fit both the total radiation sum onto the horizontal plane and the beam radiation sum onto the two-axes tracked normal plane. Thus a good agreement with measured values is ensured.

After the determination of the hourly beam and diffuse radiation densities the radiation sum on the collector (taking into account both the orientation of the collector and possible obstructions, the incident angle modifiers, the acceptance angles and the tracking mode) is determined. Eventually, either the output of the collector only or that of the collector system together with the solar fraction and the possible surplus energy is calculated by means of the SOCs and a simplified method (which avoids the determination of the initial storage conditions by means of regression parameters). These calculations need typically one (no storage tank, radiation onto collector already known) to 30 seconds (radiation values unknown, with storage).

The calculations may subsequently be modified changing the location, the orientation of the collector, the collector or storage parameters, the size and shape of incidence angle modifiers, acceptance angles, or obstructions, the user demand, the radiation processor (Liu-Jordan, Pereira-Rabl, or else), the set of SOCs, or similar.

7.4 Validation and Comparison with Other Programs

Simulation programs may be validated either with carefully monitored experiments or by comparison with a commonly accepted, well validated simulation program. For this the logical choice is TRNSYS.

The ISFH Program was developed in close connexion with various experiments in the field of solar thermal energy conversion systems. These included very detailed collector measurements with a sophisticated solar simulator (/42/) as well as domestic hot water systems (TASK VI installation "Solarhaus Freiburg" and other experiments performed at DLR, Stuttgart and ISFH, Hannover), industrial process heat systems (joint German-Mexican project SONNTLAN), and Solar Power Plants (IEA SSPS Project, Almeria, Spain). Thus sufficient comparison with experiments was granted.

The ISFH results were furthermore repeatedly checked with TRNSYS. The last investigation (1991, TRNSYS version 12.3, /43/) modelled various solar energy systems and compared the results. The agreement was basically excellent, but in some cases distinct differences arose. As an example, Fig. 7.5 shows the solar fraction of a domestic hot water system (climate: Braunschweig, Germany) depending on various key values. TRNSYS and ISFH agreed well with variations of collector area, storage volume, and heat exchanger size, but not so with that of the specific mass flow rate. In order to check this point both a standard and a low flow SDHW system have been built and carefully monitored for 15 months within TASK XIV of the IEA SH&C Programme: the results agreed perfectly well with the ISFH predictions (/44/). Thus the far more reserved ISFH predictions with regard to the increased solar fraction rates of low flow collector systems have been validated at least in this case.

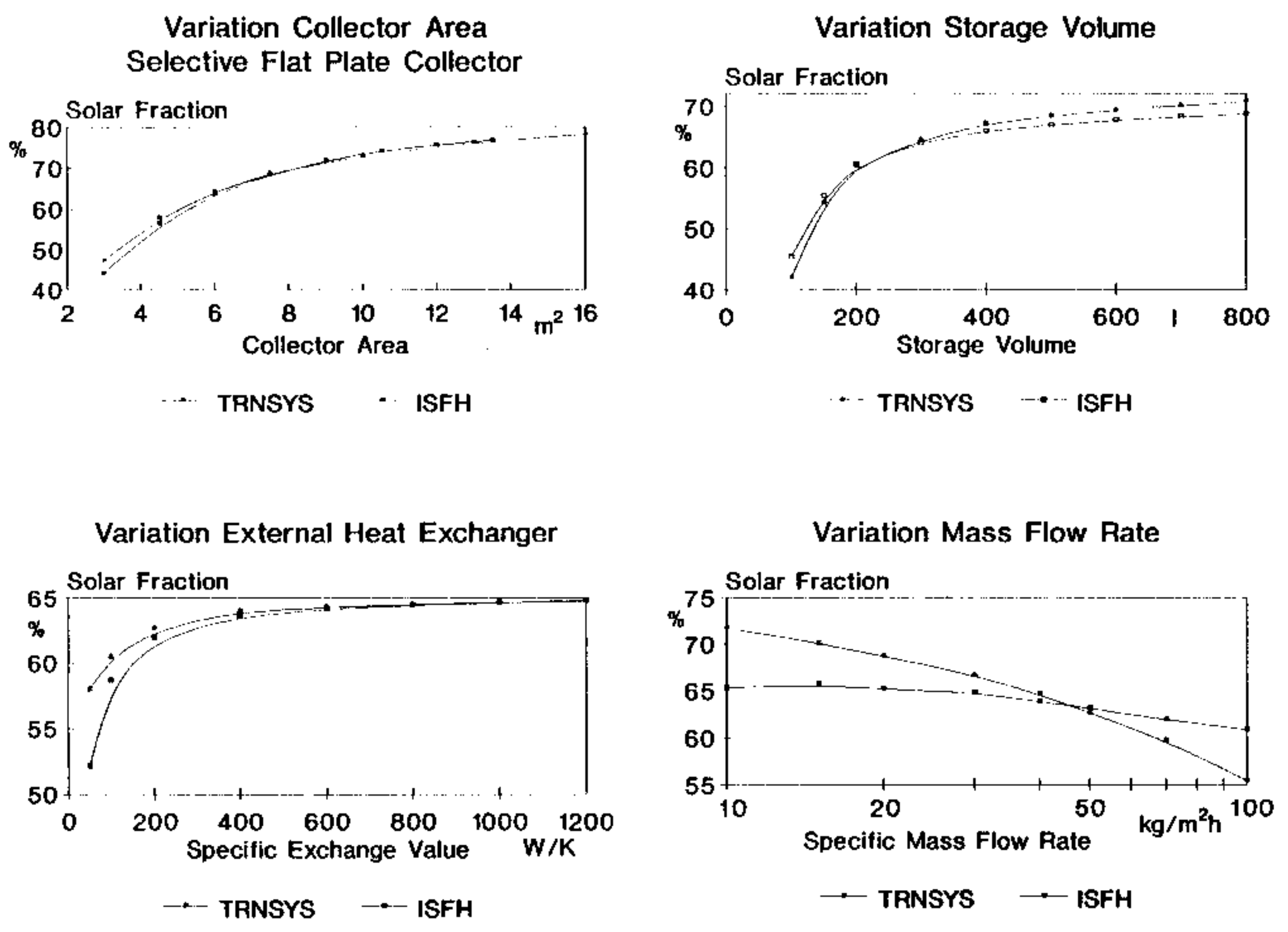


Fig. 7.5 Solar Domestic Hot Water System (Braunschweig Meteo Data)
TRNSYS and ISFH Results

7.5 Examples

Example 1: Collector with Constant Inlet Temperature

We consider the annual output of various collectors with constant inlet temperature (no piping nor heat exchanger, infinite demand) for two locations (Freiburg, F.R.G. and Ft. Collins, Co., USA). The collector parameters are given in Table 7.2, the relevant output values in fig. 7.6. The collector orientation is due South with the in-

Table 7.2 Parameters of the Investigated Collectors

Abbreviations

IAM incidence angle modifiers
AAA azimuthal acceptance angle
TS1 one-axis tracking system necessary
E/W East-West mounted, altitudinally tracked
N/S North-South mounted, azimuthally tracked (inclined axis)

- A - collector types

type	label	abbr.	remarks
C1	standard flat plate collector	FPC	
C2	selective FPC	sFPC	
C3	ditto, with flat convection barrier	isFPC	
C4	ditto, with honeycomb cony. barrier	HCC	IAM reduced
C5	evacuated tubular collector	ETC	
C8	ETC with internal CPC	ETC/CPC	AAA = ±35°
C10	improved PTC (1988)	iPTC	AAA = 1.5°, TS1

- B - collector parameters

ambient temperature 20 °C, wind velocity 2 m/s

coll. type	$\tau\alpha$	G_{int} W/m²K	C_{col} kJ/m²K	Stagnation Temperatures with Relevant Radiation Density 1000 W/m²	750 W/m²	500 W/m²
C1	.84	500	14	112	92	73 °C
C2	.82	500	14	138	114	87 °C
C3	.76	500	14	166	138	106 °C
C4	.82	500	10	225	190	148 °C
C5	.70	500	6	270	226	175 °C
C8	.68	250	5	384	329	265 °C
010	.68	150	4	563	485	395 °C

clination angle equal to latitude minus 10° (tracked collectors horizontal). With parabolic trough collectors it has to be be taken into account that North-South or two-

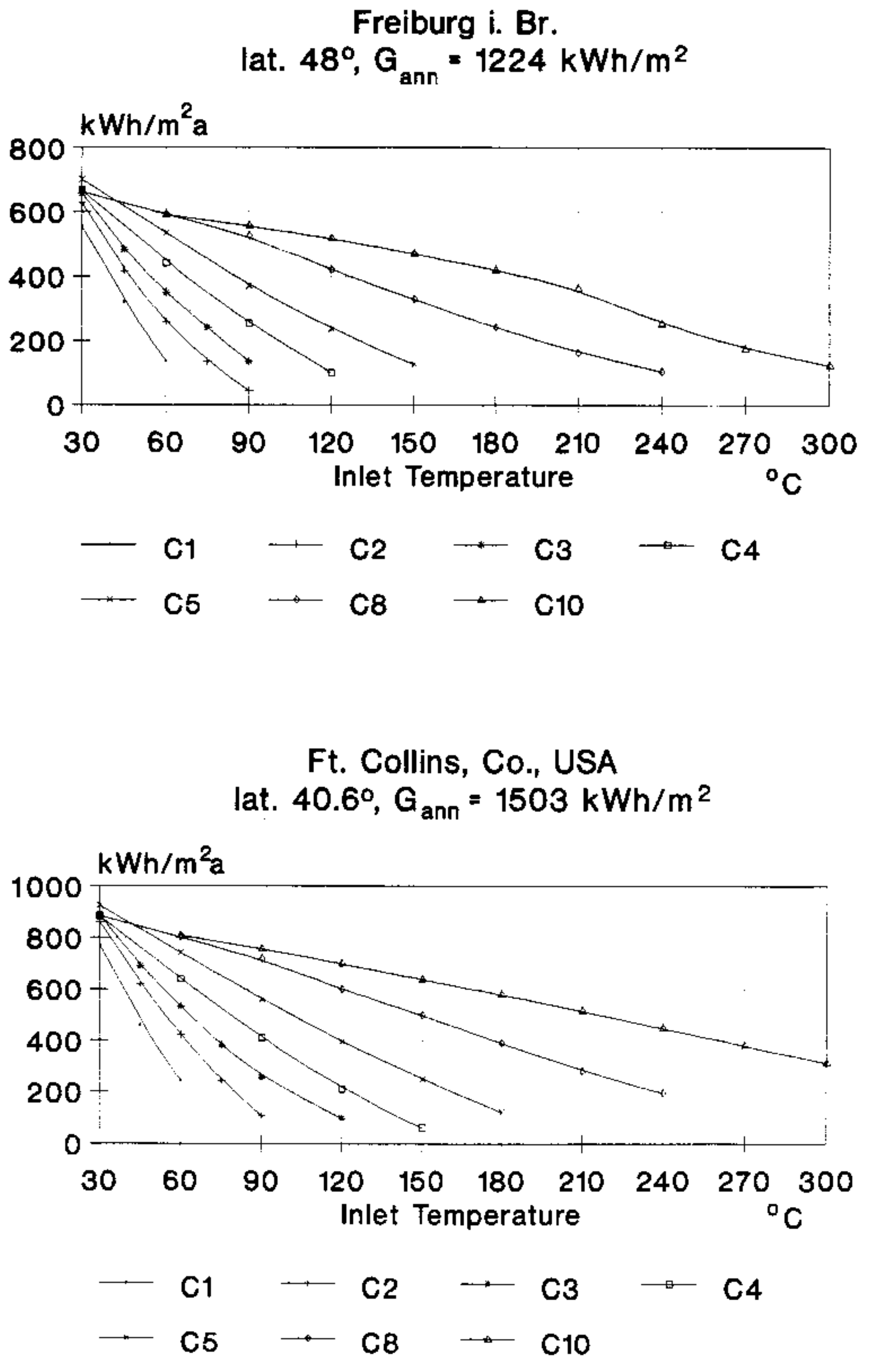


Fig. 7.6 Specific Collector Output Depending on (Constant) Inlet Temperature

axes tracking generally involves a wider spacing, thus extended piping and higher losses, which are not considered with these "collector only" values.

Although the collector output with constant inlet temperature and no piping is certainly not a very realistic value, it gives nevertheless a good impression as to the suitability of the different collector types for various applications.

Example 2: District Heating System

We now investigate a district heating system, which in fact is a favorable application for solar energy (/45, 46, 47/). We assume a 2000 m^2 collector field (either C2 or C5, resp.) with twice 250 m main piping and a total of 2400 m manifolds, water/antifreeze solution in the primary and water the in secondary circuit. The flow velocities are 2 m/s in the main piping and 1 m/s in the manifolds. The collector field is connected via a heat exchanger to the return line, the demand temperature is 30 °C in summer and 50 °C in winter. The collector orientation is due South (no shading).

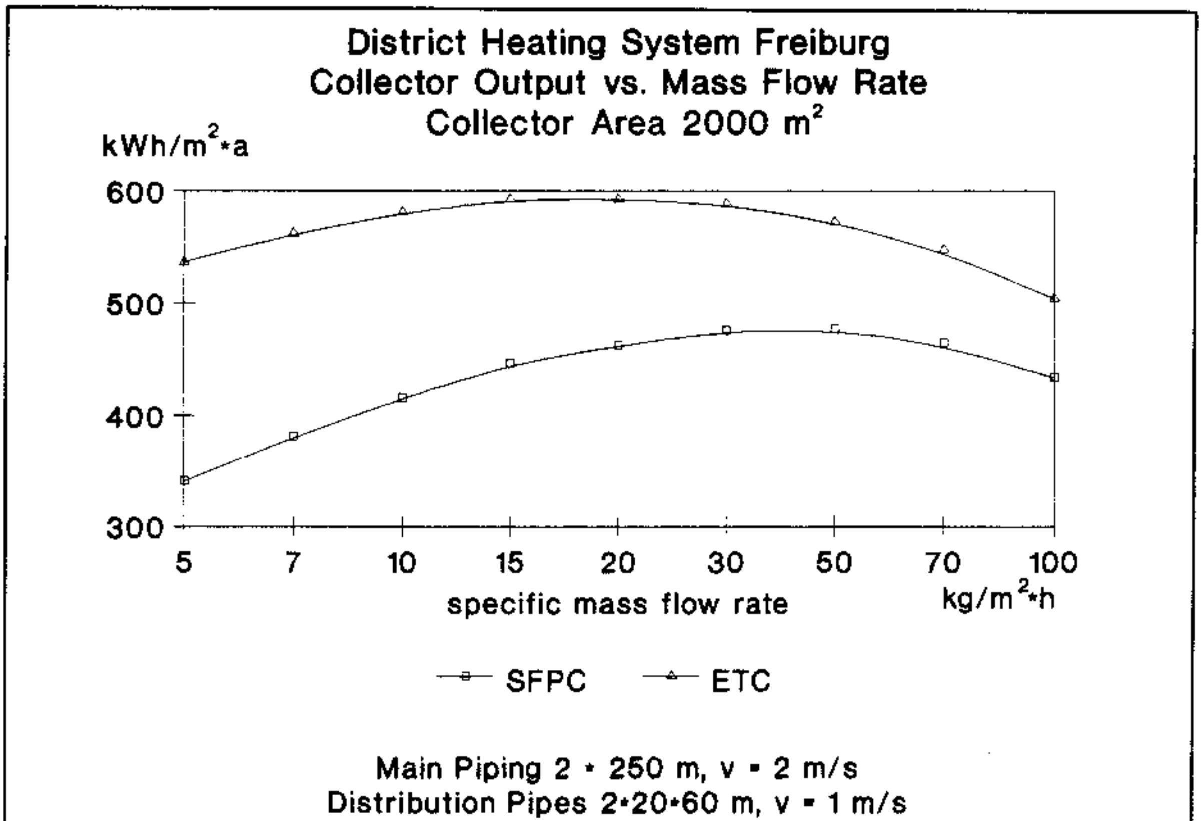
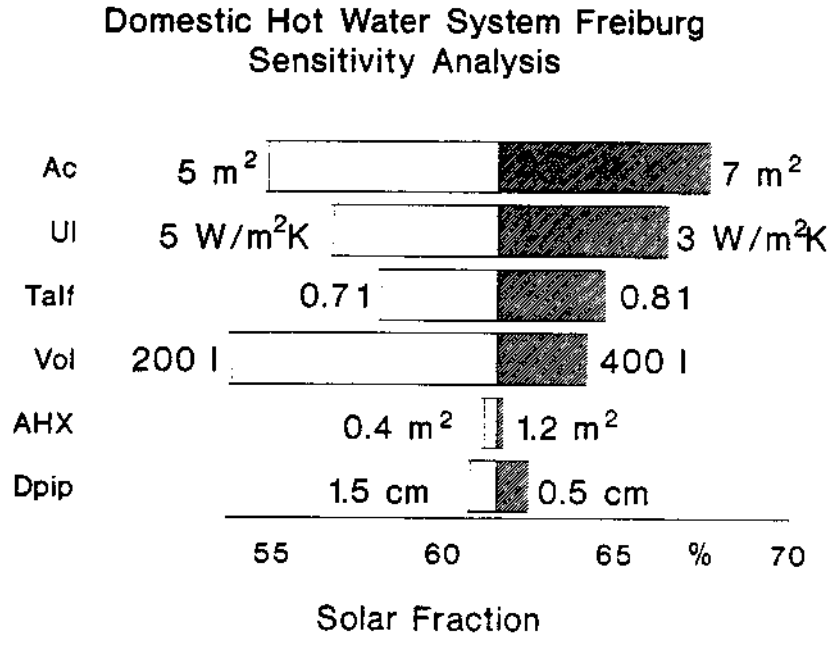


Fig. 7.7 District Heating System Freiburg i. Br.
Specific Collector Output vs. Specific Mass Flow Rate

The specific collector output for different specific mass flow rates and inclinations is given in fig 7.7 for Freiburg weather data. The optimum specific mass flow rates amount to approximately 40 kg/(m^2*h) for the selective flat plate collector and 20 kg/(m^2*h) for the evacuated tubular collector; however, as the additional losses with half that value amount to only in the order of a few percent, we strongly recommend a reduced specific mass flow rate in order to save investment costs (piping, valves, pumps) and auxiliary energy.

Example 3: Domestic Hot Water System

The last example is a sensitivity analysis of a solar domestic hot water system with selective flat plate collector, piping (2 * 14 m), external heat exchanger and stratified storage tank. The results are presented in fig. 7.8. With the "standard design" a solar fraction of 62 % is obtained. This value is rather sensitive to modifications of the collector (area, U_l-value, $\tau\alpha$-value) or the storage tank values, but only marginally to those of the heat exchanger area or the diameter of the piping.



Standard Design

Ac	Collector Area	6 m^2
Uc	Thermal Loss Value	4 W/m^2 K
Talf	Optical Efficiency	0.76
Vol	Storage Volume	300 l
AHX	Heat Exchanger Area	0.8 m^2
Dpip	Diameter of Piping	1 cm

Fig. 7.8 Solar Domestic Hot Water System (Hannover 1989)
Sensitivity Analysis of Key Parameters

8. Results of the TASK VI Modelling Workshop

The Solar Applications Lab, Colorado State University, Ft. Collins, Col., organized a model validation workshop in June 1989, in order to compare the results of different modelling approaches. The following models were presented

model/abbrev.	*presenting organization*
f-chart (FC)	SERI, Golden, Col., USA,
G^3 (G3)	University of Geneva, Switzerland,
ISFH (IS)	Institut für Solarenergieforschung, Hannover, F.R.G.,
MINSUN (MI)	Studsvik, Sweden,
TRNSYS (TR)	University of Wisconsin, Madison, Wisconsin, USA,
WATSUN (WT)	University of Waterloo, Waterloo, Ontario, Canada.

The results of the workshop are comprised in (/48/).

Three different collector systems were investigated in the course of the workshop, i. e. two DHW systems (including the pre-workshop case) and an IPH system. The pre-workshop case (DHW system with both FPC and ETC) was distributed early in 1989. With this, a special (rather unrealistic) system design was chosen (low optical efficiencies, high capacitances, etc.) in order to investigate the limitations of the different models. However, some participants did not receive the messages in time and there were, furthermore, some misinterpretations. Hence the results of the pre-workshop case studies were comparable only in a very limited way. The participants felt furthermore, that the modelling should start from very simple systems (horizontally mounted collector with both fully mixed solar and hot water tank, no piping nor heat exchanger), and additional features should be investigated only afterwards.

The f-chart operator was available only for a limited time, thus some results were missing or only supplied after the workshop. MINSUN was developed primarily for systems with very large (seasonal) storage tanks, thus it was not applicable for all investigations. G^3, ISFH, TRNSYS, and WATSUN were not subject to those restrictions. The number of the performed calculations is shown in Table 8.1.

TRNSYS is the most widely spread, accepted, and validated of those models. Furthermore, by its inherent structure, it shows the highest flexibility, as new features may be modelled by the operator himself by writing the respective codes. Thus TRNSYS was intended to act as landmark for the other programmes. However, it revealed shortly, that both input procedure and calculation time were too long for such a "Modelling Race", so that only a few calculations could be performed in time. It showed furthermore, that the input structure of TRNSYS is so complex, that within a hurry even the related experts could easily perform some mistakes and that the results had to be corrected repeatedly. Even now not all TRNSYS results seem to be correct. Thus the suitability of TRNSYS is restricted in some degree, and the results of the different calculations have often to be compared mutually.

Table 8.1 Models, Systems, and Number of Performed Calculations

Model \ System	SDHW	IPH fixed collectors	IPH tracking collectors	Sum
f-chart	13(+7)	12	(+12)	25(+ 19)
G3	25	24	-	49
ISFH	25	30	30	85
MINSUN	11	-	-	11
TRNSYS	7(+ 14)	-	-	7(+14)
WATSUN	25	4	-	29

Comment: number of the calculations supplied after the workshop in brackets

For the solar domestic hot water system a new base case (Miami, selective flat plate collectors, two storage tanks, demand 59 MJ/d) was defined. The following features were investigated successively and, sometimes, jointly:

- different collector areas
- piping effects
- stratification and flow rate effects
- both tanks combined into one
- different climatic conditions (Miami, Seattle, and Albuquerque)
- different collector tilts
- added details to the collector description
- low and high performance collectors
- different demand temperatures and load profiles
- heat exchanger effects
- incident angle modifiers.

Examples are given in figs. 8.1 and 8.2. Experiment #3, the new base case is shown in fig. 8.1. We included within this figure the original (1 st day of workshop) and corrected (4th day) TRNSYS results in order to demonstrate the range of possible errors. More important is surely experiment #15, which combines all the above mentioned features. The results may be comprised in the following way:

- the results of the different programmes are virtually "similar", i.e., they show the similar trends; however, there are certain deviations which base on different as sumptions as radiation processors, models of the collector or storage tank, etc.; some of these assumptions have been adjusted meanwhile,
- the different programmes may be best compared in proceeding from a very simp- le base case to complex systems by adding successively new features and investigating the respective effects,

- it is impossible to validate this procedure by experiments,
- validation by experiments is only possible in a few cases with particular experiments,
- an accurate, well and widely validated simulation model is best suited as validation tool for other programmes; at present, the logical choice of such a model seems to be TRNSYS,
- TRNSYS has to be given a prolonged time to treat the respective problems, and its results have to be carefully checked (Figs. 8.1, 8.3),
- the results of G^3 and ISFH agree excellently, whereas the WATSUN results show typically a higher output and solar fraction; the MINSUN results show a completely different seasonal behaviour.

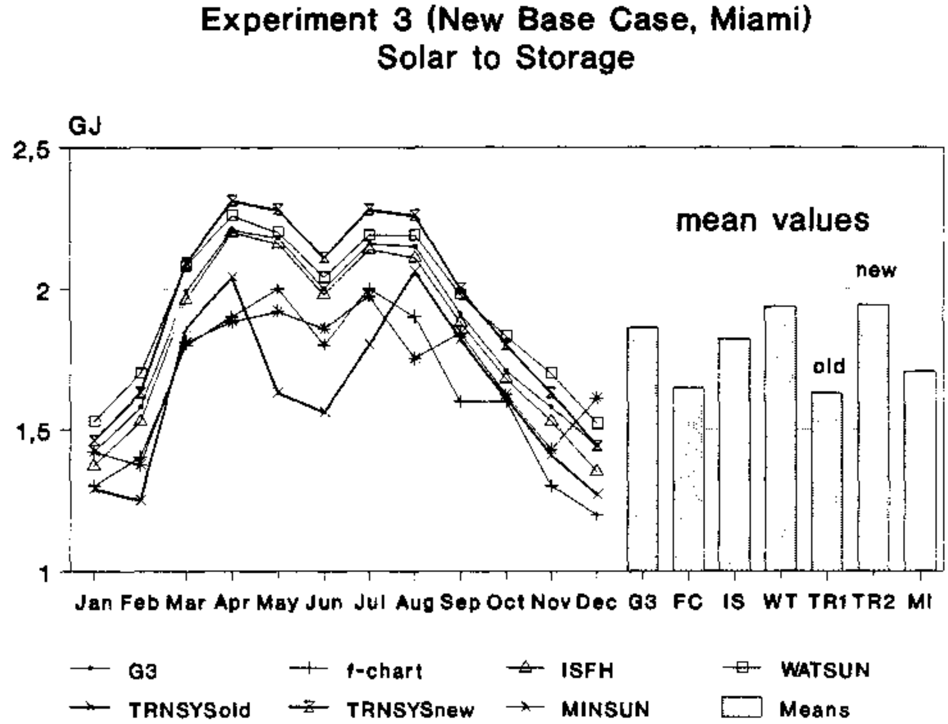
Within the discussion of the results it was pointed out, that the (constant) cold water inlet temperature of 10 °C is surely not realistic for Miami; the inlet temperature should rather conform to the mean annual ambient temperature, which is approximately 22°C. Thus, during operation, the cold water was usually preheated and the effects of increased piping and/or collector capacitances could only incompletely established.

The next case was an industrial process heat installation with a demand of 1500 kWh/day (temperatures 115/85 °C). Both ETC and PTC (these last ones either East-West oriented, altitudinally tracked, or North-South oriented, inclined to latitude, azimuthally tracked) with areas of up to 1000 m^2 should be combined with a storage tank (either 50 m^3 or 100 m^3) to meet the demand. The piping consisted of 2*160 m from the storage tank to the collector field and the interconnecting pipes of the loops.

These investigations revealed substantial differences as to the operation time for both input procedure and calculation. ISFH was by far the quickest method, finishing first in completing 60 different calculations, i.e. the ETC installations with both 50 m^3 and 100 m^3 storage tank, and the two PTC (E/W and N/S mounted) ones with 50 m^3 storage tank (the calculation of the PTC systems with 100 m^3 tank was omitted, as the respective differences revealed to be minute in the ETC case). The other programmes treated initially only the ETC installations, as the different tracking methods caused some difficulties: G^3 completed 24 cases, f-chart 12 (f-chart supplied after the workshop 24 more results for the tracked collectors as well, but as these show identical values for both orientations/tracking methods, they are surely not correct), and WATSUN 4. Thus only a limited comparison of the different models is possible.

The influence of the storage volume has been only investigated by ISFH and G^3. The trend of both programmes is very close and shows, that the advantage of a larger storage tank is irrelevant for all cases. We present here the results for Seattle, as the differences are best pronounced in a variable climate (fig. 8.3).

The solar fraction rates of the ETC installations are shown in figs. 8.4a..c. WATSUN results were only available for Miami and show very high values. As to the other



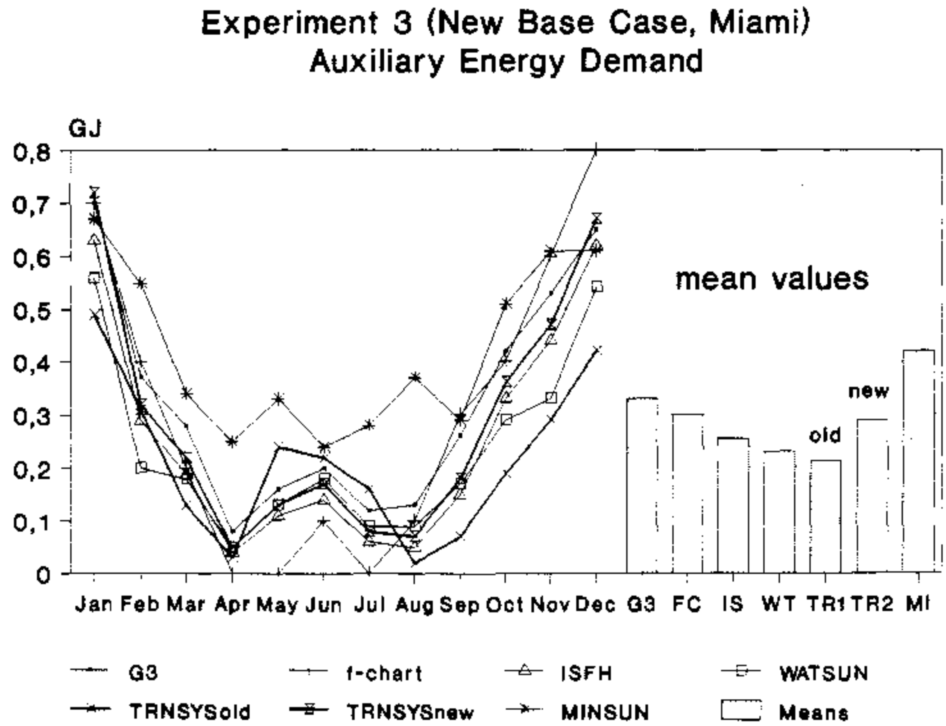
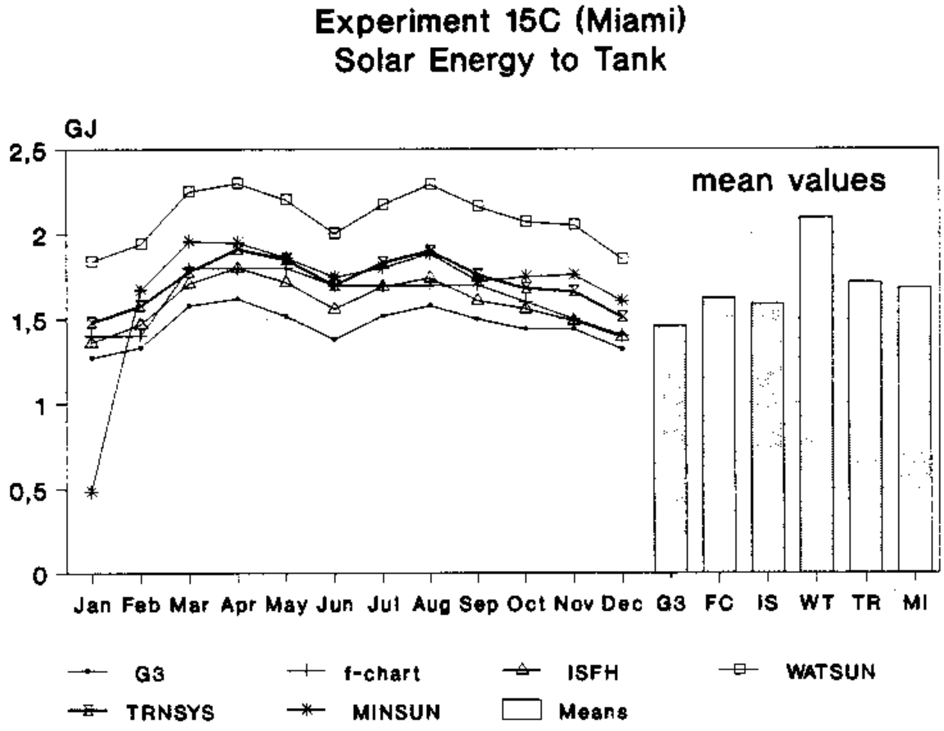


Fig. 8.1 Solar Domestic Hot Water System: New Base Case (Exp. 3)
Solar Energy to Tank and Auxiliary Energy Demand (Miami)



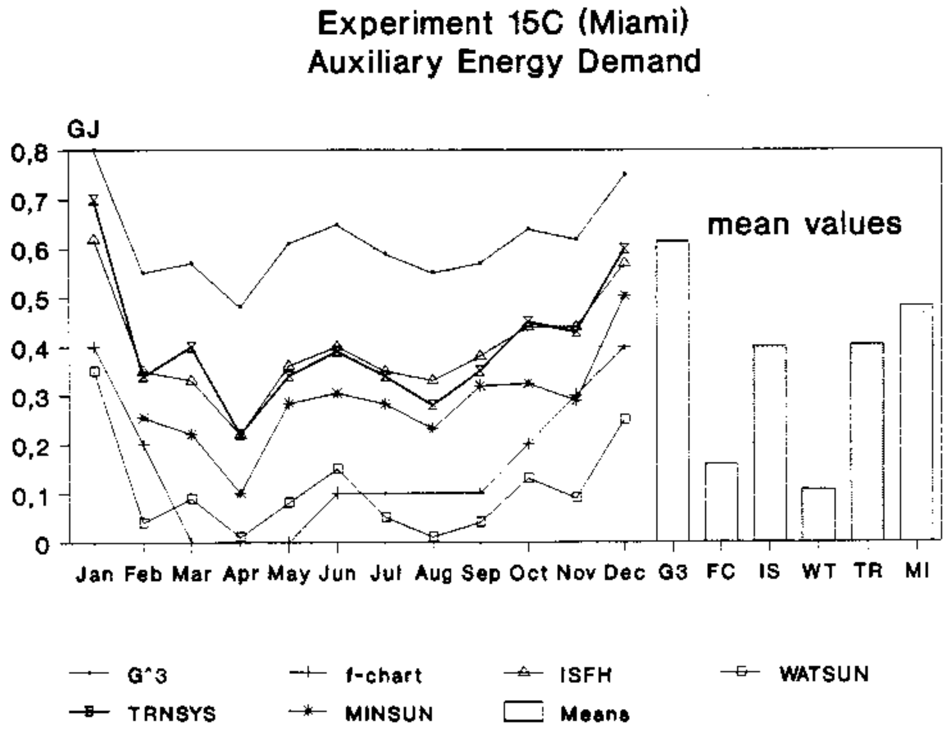


Fig. 8.2 Solar Domestic Hot Water System: Experiment 15A
Solar Energy to Tank and Auxiliary Energy Demand (Miami)

models, G^3 takes always the highest, f-chart the lowest, and ISFH the intermediate position.

The solar fraction rates of the IPH installations using tracking collector were only investigated by ISFH and f-chart. Two of them are shown in fig. 8.5 a. b. f-chart shows very high solar fraction rates in all these cases; however, as E/W and N/S oriented collector rows give identical results, either the programme itself or its application was wrong. Thus we have to restrict on the ISFH results. They show, that with this application the parabolic trough collector is surely the best choice in dry, clear climates (Albuquerque), whereas the evacuated tubular one may be competitive with intermediate solar fraction rates in more humid climates with high diffuse part (i. e. Miami)

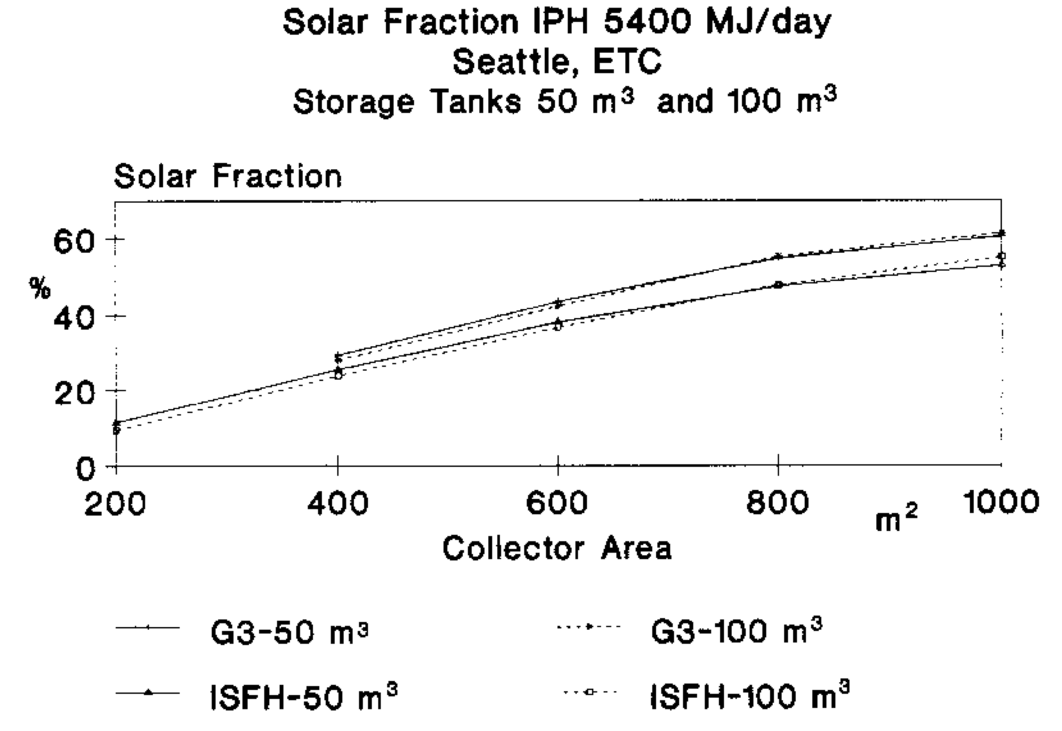


Fig. 8.3 Industrial Process Heat Installation (Seattle)
Variation of Storage Volume (50 m^3 and 100 m^3, G^3 and ISFH)

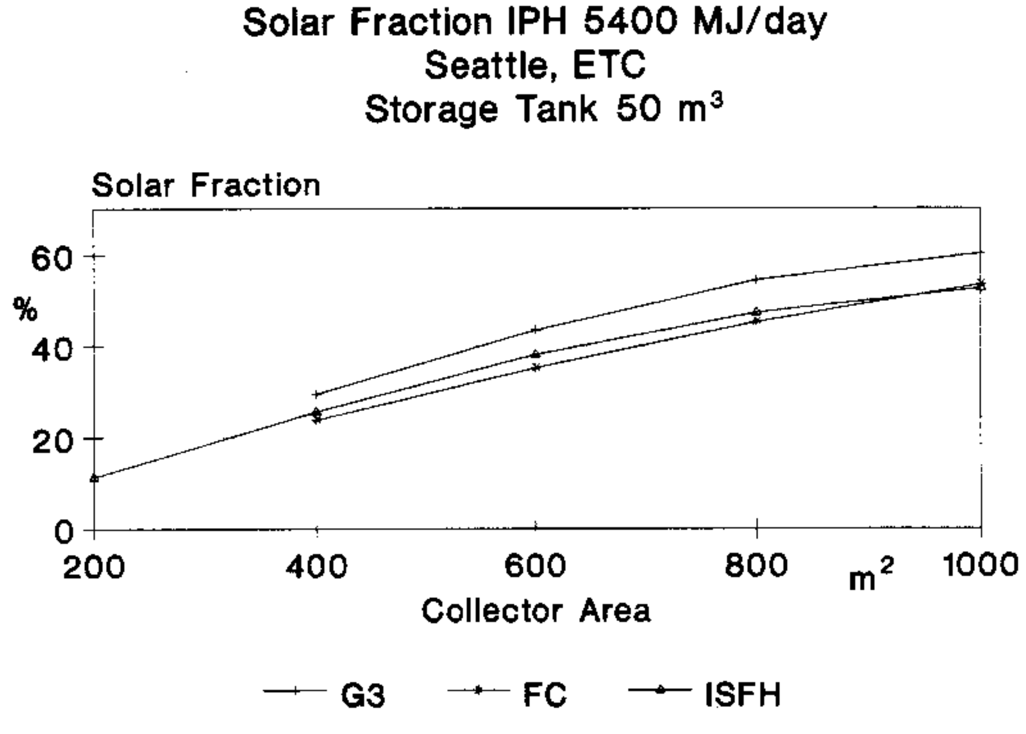


Fig. 8.4 a Industrial Process Heat Installation: Solar Fraction Rates (Seattle) Evacuated Tubular Collectors (G^3, f-chart, ISFH)

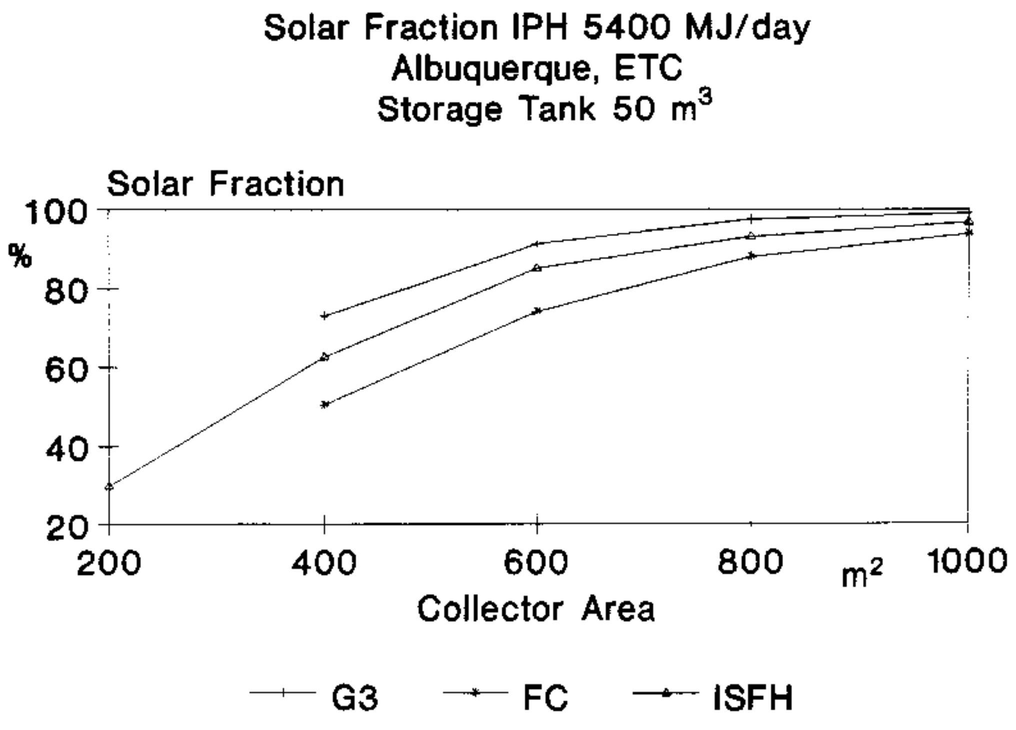


Fig. 8.4 b Industrial Process Heat Installation: Solar Fraction Rates Albuquerque: Evacuated Tubular Collectors (G^3, f-chart, ISFH)

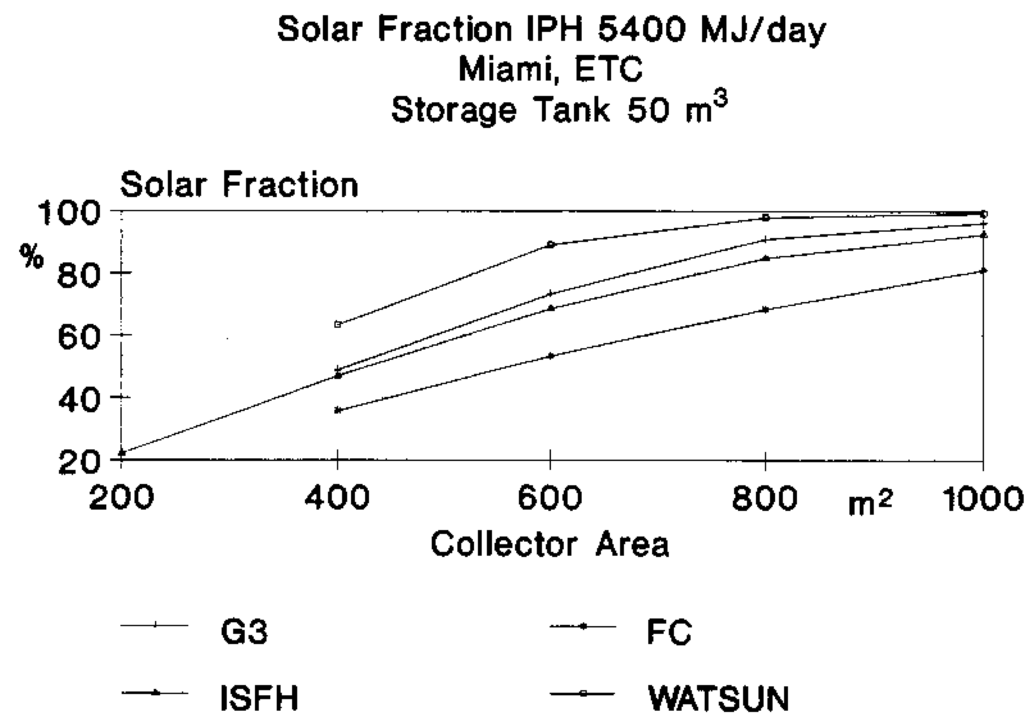


Fig. 8.4 c Industrial Process Heat Installation: Solar Fraction Rates (Miami) Evacuated Tubular Collectors (G³, f-chart, ISFH, WATSUN)

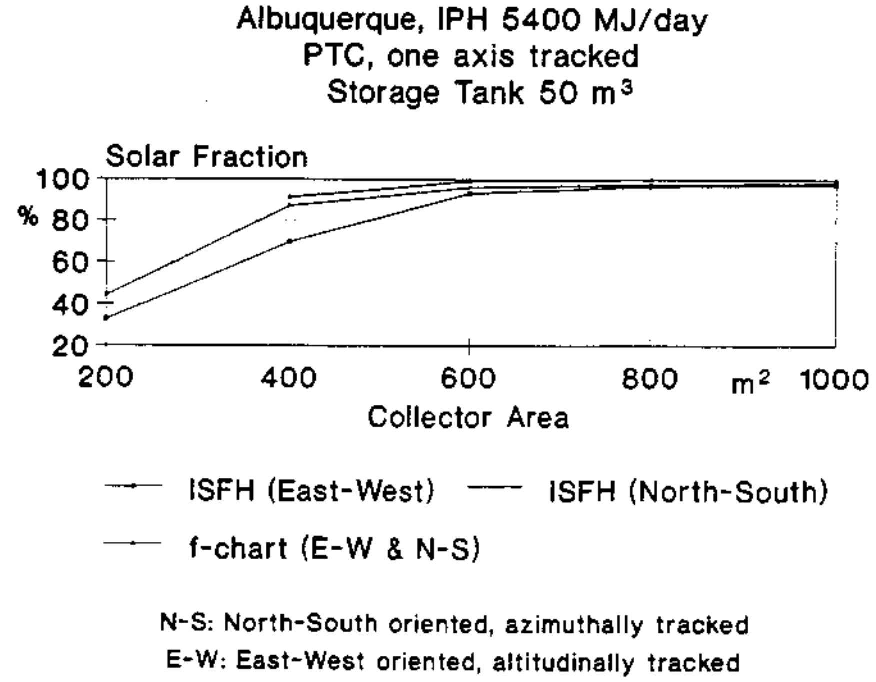


Fig. 8.5a Solar Fraction Rates of Solar Industrial Process Heat Installation Using Parabolic Trough Collectors with Different Orientations and Tracking Systems (Albuquerque, ISFH and f-chart)

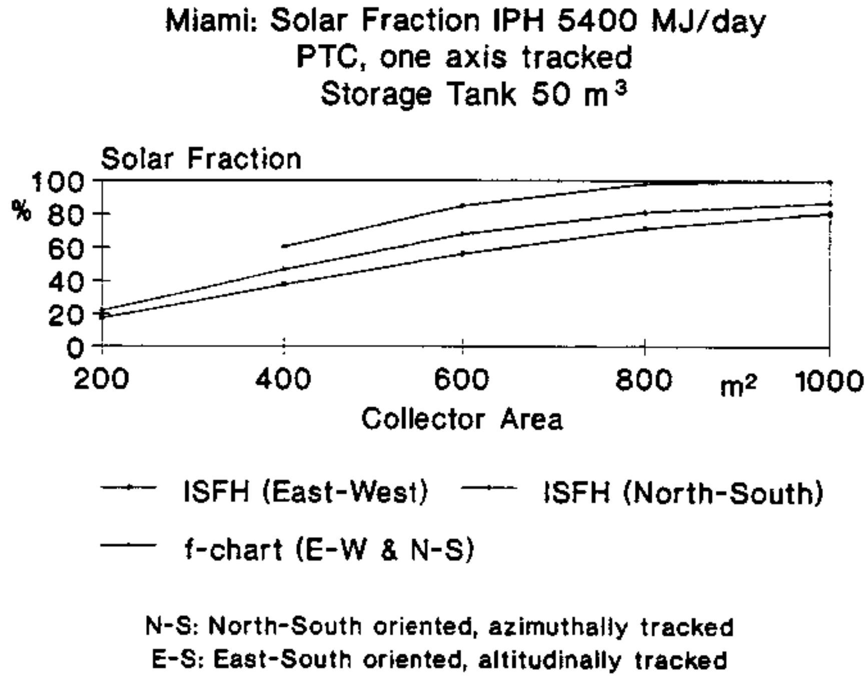


Fig. 8.5b Solar Fraction Rates of Solar Industrial Process Heat Installation Using Parabolic Trough Collectors with Different Orientations and Tracking Systems (Miami, ISFH and f-chart)

9. Summary and Conclusions

The design of active solar energy systems is frequently done either with rules of thumb, empirical facts, or with very simple equations and diagrams. Thus a reliable assessment of the collector output and solar fraction is often impossible, to say nothing of a serious optimization of the plant (unconventional design, novel features, collector selection, dimensioning of components, operational parameters etc). There are certainly detailed models available to do this job, but they are both expensive in the instruction and application phase and only very seldomly used in the design work. Thus solar energy systems are often not optimized and do not reach their theoretical potential of performance.

During the Task VI activities of the IEA Solar Heating and Cooling Programme a concerted action was initiated to investigate analytically the experimentally found Input-/Output-Diagrams. Their formation was widely discussed and, especially, the parameters influencing the form, X-shift and slope of the curves were examined. Later on the analytical generation of those curves and their comparison with experimental ones came more in the foreground. Finally different design methods, looking far deeper into the details, have been developed and validated both with experiments and TRNSYS. It has been shown that the results differ only marginally from those of conventional, component oriented models. The main findings of these activities are

- for most solar energy systems there exist system operational characteristics (SOCs) connecting the most interesting output values with design/input values,
- these SOCs may be generated easily by means of detailed programs,
- the determination of the collector output, solar fraction and other relevant oper ational parameters by means of these SOCs may be very accurate for a wide range of operational parameters and climatic regions.

However, our investigations clearly identified some serious gaps in the experimental area, which have to be closed in the interest of future applications. Especially important are the so-called "secondary collector parameters" as e.g. the temperature dependence of the thermal losses, the dependence of the absorber-fluid conductivity, and the incidence angle modifiers. Yet these parameters may quickly grow to primary importance in applications with an extended temperature range such or with improved collector constructions.

The careful analysis of our and related experiments shows, that the technological limits have been very seldomly reached, and that considerable improvements are further on achievable, both with components and systems. Herewith, the convection suppression with flat plate collectors, internal CPCs with evacuated tubular col lectors and/or improved storage tank concepts, may play a similarly important role as the consistent system optimization including variable flow concepts, piping reduction and other. However, all these activities have to be performed in close connection with a simulation model taking into account all these "secondary" effects.

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