



FORSCHUNGS- UND TESTZENTRUM FÜR
SOLARANLAGEN

Institut für Thermodynamik und Wärmetechnik
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in Kooperation mit



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DEVELOPMENT OF A PROCEDURE FOR
EXTRAPOLATING PERFORMANCE TEST RESULTS
OF ONE SOLAR DOMESTIC HOT WATER
(DHW) SYSTEM TESTED TO SYSTEMS OF THE
SAME TYPE BUT DIFFERING IN SIZE

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List of Symbols

a_1	heat transfer coefficient	[W/(m ² K)]
a_2	temperature dependent heat transfer coefficient	[W/(m ² K ²)]
$a1...a8$	Parameters	[-]
A_c	Collector Area	[m ²]
C_{eff}	Effective heat capacity	[J/K]
f_{sol}	Solar fraction	[-]
G	Solar Irradiance	[W/m ²]
ϑ_m	Mean collector temperature	[°C]
V_{sto}	Store volume	[m ³]
z^*	Relative position of temperature sensor	[-]
Δf_{sol}	Difference between the values of the solar fraction obtained by the DST-method and the calculation method for one specific system	[-]
ΔF_{sol}	Summation over Δf_{sol} for all the systems that have been measured with the DST-method	[-]
ε	Discrepancy	[-]
η	Collector efficiency	[-]
η_o	Conversion factor	[-]
ϑ_a	Ambient air temperature	[°C]

List of Abbreviations

<i>ITW</i>	Institut für Thermodynamik und Wärmetechnik, Universität Stuttgart (Institute for Thermodynamics and Thermal Engineering – University of Stuttgart)	Stuttgart, Germany
<i>INETI</i>	Instituto Nacional de Tecnología Industrial, Portugal	Lissabon, Portugal
<i>CSTB</i>	Centre Scientifique et Technique du Bâtiment	Sophia Antipolis, France

1. Introduction

Today, each and every system configuration of a solar domestic hot water system (DHW) has to be tested by an accredited testing laboratory in order to get the “Solar Keymark” certification. Often, companies offer a product line of their solar DHW systems. A product line can be described as a series of hot water systems that are identical with regard to their construction and only differ in their collector and storage dimension. An identical construction is given if the set-up of the system is similar (pipes, electrical pump, hydraulic connections, type but not mandatorily size of the heat exchanger ...), the insulation concept is similar (material, thickness) and the collectors installed are from the same type. With the assumption that the thermal performance of a solar DHW system is based on the construction design, the thermal behaviour of a system can be described as a function of size. Then, within a product line the thermal behaviour only depends on size.

Due to the relatively cost- and time-intensive procedure of the testing it is not acceptable for the companies to test each of their systems. Hence, it is desirable to have a calculation tool that is able to predict the solar fractions of the whole product family without having to test each of the system configurations.

The aim of this work carried out within the Solar Keymark II Project is to develop a procedure with which it is possible to extrapolate the performance test results obtained by only one system tested to the other systems of the same product line. This paper presents the results of the work. In the first sections the mathematical model of the calculation tool will be described. In the next section the accuracy of the model will be assessed. The thermal performance of different thermosiphon DHW systems of one product line has been tested at three labs (INETI, CSTB, ITW). These test results will be compared to the results achieved by the mathematical model. In the last chapter the results of this comparison will be discussed.

2. Setting up a mathematical model

The idea is to set up an equation that establishes a relationship between the solar fraction f_{sol} of a solar hot water system and the collector aperture area (A_c) and the store volume (V_{sto}),

$$f_{sol} = f(A_c, V_{sto}) \quad (2.1)$$

The function f_{sol} has to fulfil two criteria: it has to be a good approximation to the real behaviour of the system and it has to be a function that can be solved directly.

In a first step the simulation software TRNSYS was used to identify the influence of the collector size and the storage volume on the solar fraction. The simulation software has the advantage that a parameter variation can be performed easily and relatively quickly. A domestic hot water system as it can be seen in Figure 2.1 will be simulated with TRNSYS. It is a thermosiphon system with the store on the roof and without auxiliary heating. The collector aperture area of this system varies between 2 m^2 and 8 m^2 in steps of 1 m^2 and the storage tank volume varies between 0.2 m^3 and 0.6 m^3 in steps of 0.1 m^3 . The main parameters describing the system are summarised in Table 2.1.

Table 2.1: Main parameters of the system

Location	- Athens
Piping	- no piping (piping is neglected)
Collector	<ul style="list-style-type: none"> - Alignment: South, 45° - Performance parameter: cf. chapter 6 - Aperture area: $2 \dots 8 \text{ m}^2$
Storage	<ul style="list-style-type: none"> - Volume: $0.2 \dots 0.6 \text{ m}^3$ - Heat loss rate: cf. chapter 6 - Store ambient temperature : outside temperature
Hot water demand	<ul style="list-style-type: none"> - 110 l/d, 200 l/d, 300 l/d - Demand Temperature: 45°C - Cold water temperature: $T_{\text{average}} + \Delta T_{\text{average}} \sin(2\pi(d-137)/365)$ <ul style="list-style-type: none"> o Athen $T_{\text{average}} = 17.4 \quad \Delta T_{\text{average}} = 7.4$

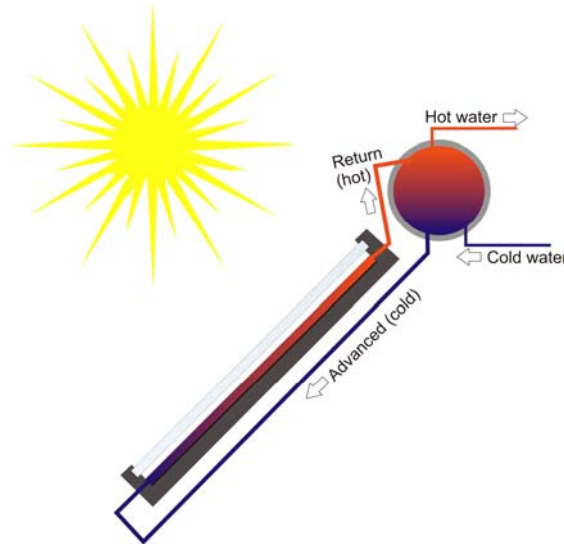


Figure 2.1 Domestic hot water system simulated with TRNSYS

In Table 2.2 f_{sol} -values calculated for a thermosiphon system at the location of Athens and a hot water consumption of 200 l/d are displayed for different sizes of collector aperture area A_c and storage tank volume V_{sto} .

Table 2.2 Solar fractions f_{sol} computed with TRNSYS for a product line of solar hot water systems which differ in their collector aperture area and their tank volume

A_c/V_{sto}	0.2 m ³	0.3 m ³	0.4 m ³	0.5 m ³	0.6 m ³
2 m ²	0.591	0.582	0.572	0.563	0.556
3 m ²	0.702	0.696	0.686	0.678	0.671
4 m ²	0.764	0.762	0.757	0.751	0.748
5 m ²	0.803	0.803	0.799	0.796	0.794
6 m ²	0.831	0.832	0.829	0.826	0.824
7 m ²	0.852	0.854	0.851	0.849	0.848
8 m ²	0.868	0.872	0.870	0.867	0.866

With increasing collector aperture area more solar energy can be used to heat the water and less energy for auxiliary heating is needed. Thus f_{sol} increases. If the storage volume is increased the system behaviour is different. For systems with a collector area smaller than 7 m² a decrease in the energy gain with increasing storage volume can be noticed. For systems with a greater collector area the energy gain first increases with increasing storage volume and then decreases. This behaviour can be explained by the thermal losses that will increase with increasing storage volume. It can be seen that an oversized storage leads to a reduction of the useful energy gain.

In Figure 2.2 the values of f_{sol} are plotted in dependency of the collector aperture area and the storage tank volume. It can be seen that the values describe a surface in the three-dimensional space.

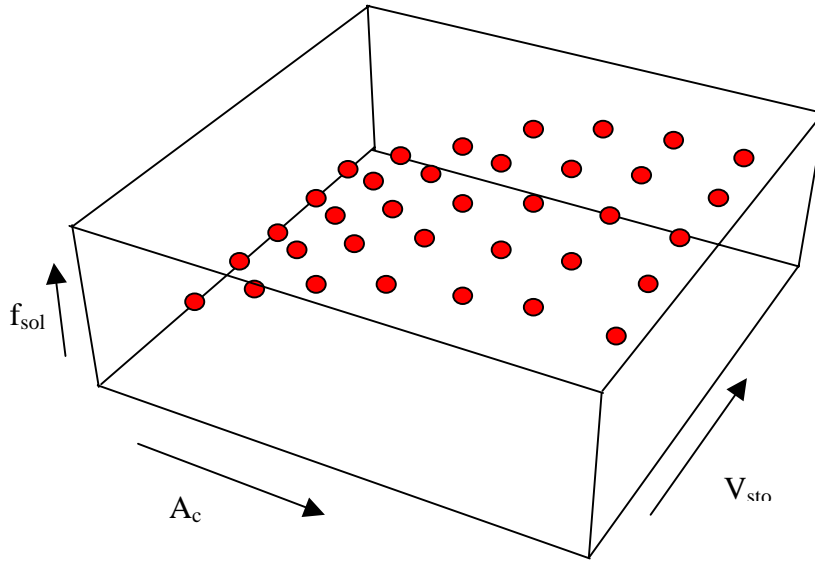


Figure 2.2: Calculated solar fraction f_{sol} in dependency of the collector aperture area A_c and the storage tank volume V_{sto}

In Figure 2.3 the solar fraction is plotted in dependency of the collector aperture area for one specific store volume, in Figure 2.4 the solar fraction is plotted in dependency of the store volume for one specific collector aperture area. The slope of the curves can in both cases be well described by a polynomial function of second order (see eqn 2.2 and 2.3), where $a_1...a_8$ are system specific parameters.

$$f_{sol}(A_c) = a_1 + a_2 \cdot A_c + a_3 \cdot A_c^2 \quad (2.2)$$

$$f_{sol}(V_{sto}) = a_4 + a_5 \cdot V_{sto} + a_6 \cdot V_{sto}^2 \quad (2.3)$$

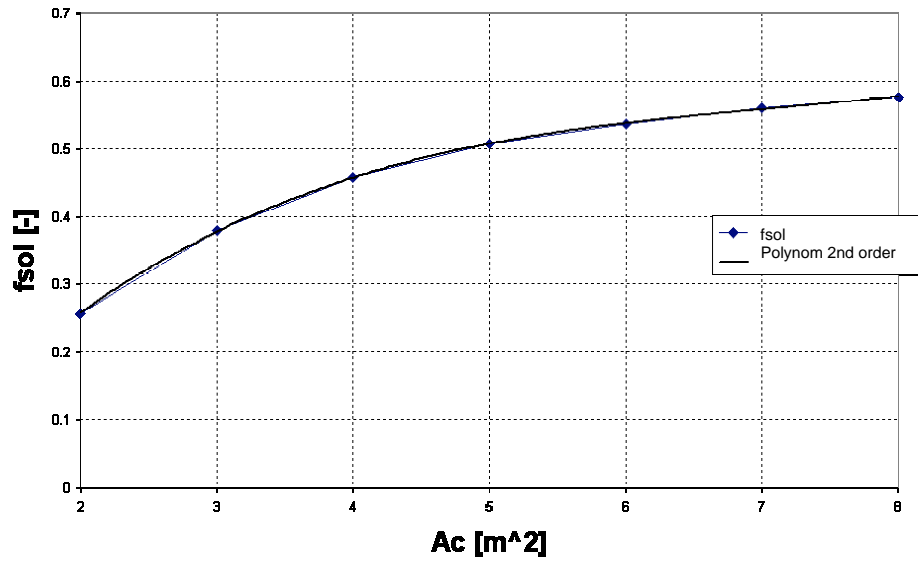


Figure 2.3: Solar fraction against collector aperture area

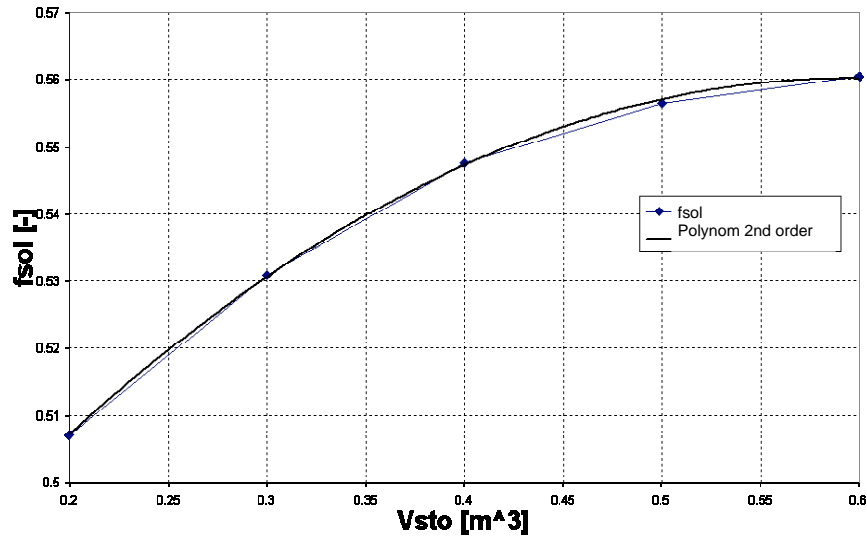


Figure 2.4: Solar fraction against storage tank capacity

The polynomial of a two dimensional function of second order $f_{sol} = f(A_c, V_{Sto})$ has the following form,

$$f_{sol}(A_c, V_{Sto}) = a1 + a2 \cdot A_c + a3 \cdot A_c^2 + a4 \cdot V_{Sto} + a5 \cdot A_c \cdot V_{Sto} + a6 \cdot A_c^2 \cdot V_{Sto} + a7 \cdot A_c \cdot V_{Sto}^2 + a8 \cdot V_{Sto}^2 \quad (2.4)$$

The values of $a1...a8$ can be determined by a regression analyses. Exemplary, the parameters $a1...a8$ have been evaluated for the system specified in Table 2.2. The corresponding surface plot of equation 2.4 is displayed in Figure 2.5.

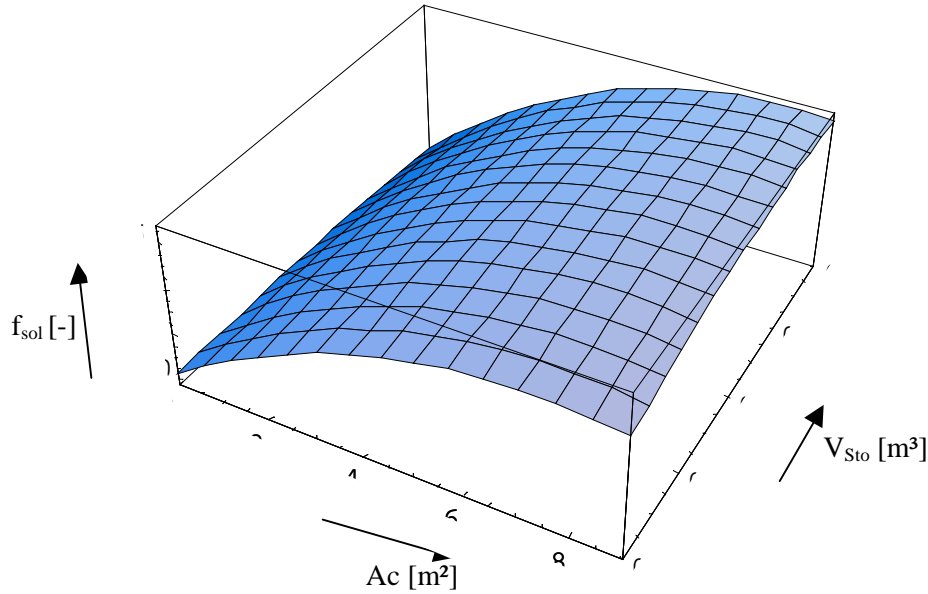


Figure 2.5: Surface plot of equation (2.4)

In order to verify the accuracy of the results of equation (2.4) the computed values of f_{sol} for the different collector aperture areas and storage volumes are compared to the results of the TRNSYS simulation. The relative discrepancy resulting from this comparison is calculated according to eqn. (2.5).

$$\varepsilon = \left| \frac{f_{sol_TRNSYS} - f_{sol_calc}}{f_{sol_TRNSYS}} \right| \cdot 100\% \quad (2.5)$$

Table 2.3 shows the relative discrepancies for each of the different system configurations. As can be seen, the maximal relative discrepancy for this product line is 2.1 % (for a collector aperture area of 3 m² and a store volume of 0.6 m³)

Table 2.3 Relative discrepancies between the solar fraction determined by TRNSYS simulations (TRNSYS) and the solar fraction computed with equation (2.4)

A_c / V_{sto}	0.2 m ³	0.3 m ³	0.4 m ³	0.5 m ³	0.6 m ³
2 m ²	0.7%	1.3%	1.6%	1.4%	0.6%
3 m ²	2.1%	1.3%	0.7%	0.8%	1.4%
4 m ²	1.6%	0.9%	0.5%	0.6%	1.4%
5 m ²	0.4%	0.4%	0.9%	0.6%	0.3%
6 m ²	0.2%	1.1%	1.7%	1.6%	0.6%
7 m ²	0.2%	0.8%	1.5%	1.3%	0.2%
8 m ²	1.7%	0.7%	0.1%	0.3%	1.5%

With equation (2.4) it is possible to calculate the solar fractions for arbitrary sizes of storage tanks and collector aperture areas for solar hot water systems of one specific product line. For each product line of different designs a new function $f_{sol} = f(A_c, V_{sto})$ has to be determined. As the simulations necessary to derive the function are pretty complex and time-intensive it is not reasonable to carry out this calculation for every product family of hot water systems on the market. Hence a different approach has to be found where the effects of collector aperture size and storage tank volumes can be calculated or at least be estimated more easily.

3. Physical properties influencing the solar fractions of a thermosiphon system

Beside the size of the collector aperture areas and storage tank volumes there are further physical parameters which have an impact on the solar fraction of a thermosiphon system. The main influence parameters are:

- Geographic position
 - Solar radiation
 - Mean ambient temperature
- Performance of the thermal collectors
 - e.g. collector efficiency
- Performance of the storage tank
 - e.g. heat losses

In order to take these different effects into account for a great variety of thermosiphon systems, the main influence parameters will be classified. Different types of storages and collectors with characteristic values representative for the European market have been chosen:

- Storage: heat loss rate
 - Very low
 - Low
 - Medium
 - High
- Collector type
 - Vacuum tube collector
 - Flat plate collector, type 1
 - Flat plate collector, type 2

More information about the specific data of these parameters can be found in chapter 7. For all combinations of the influence parameters equation $f_{sol} = f(A_c, V_{Sto})$ will be determined as described in chapter 2.

Exemplary, in Figure 3.1, the surface plots of the solar fraction f_{sol} for three different collector types are depicted. In this case the influence of the storage tanks was kept constant. It can be seen that with a variation of the collector parameters different solar fractions in dependency of collector aperture area and storage tank volumes arise.

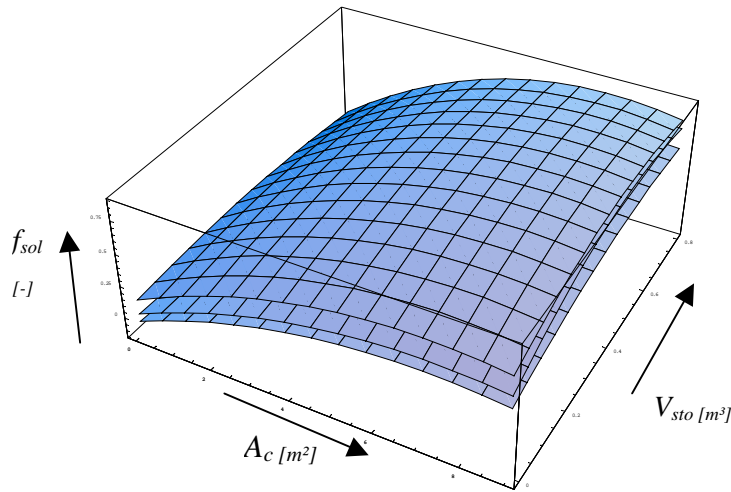


Figure 3.1: Surface plots of the solar fractions in dependency of the collector aperture area and the storage tank volume

For the following steps it will be assumed that with the parameter classification a wide range of thermosiphon systems without auxiliary heating can be described sufficiently. In the next chapter it will be presented how the appropriate surface for a specific product family can be identified.

4. Selection of the best fitting surface

By the example of the product line described in Table 4.1 it will be illustrated how to identify the best fitting surface.

Table 4.1 Example for a product line

System no.	Amount of collector modules	Collector aperture area [m ²]	Storage tank capacity [m ³]	f _{sol} [-]
1	1	2.0	0.3	0.572
2	2	4.0	0.3	0.725
3	3	6.0	0.3	?
4	1	2.0	0.5	?
5	2	4.0	0.5	?
6	3	6.0	0.5	0.830

It will be assumed that the product line consists of six DHW systems which only differ in the size of the collector area and the store volume. The solar fractions of the system 1, 2 and 6 have been determined based on measurements according to the DST method and on a long term performance prediction for the location of Athens and a hot water consumption of 200 l/d. The solar fractions of the systems 3, 4 and 5 are not known a priori and have to be calculated by the procedure described in chapter 2. To illustrate the general approach of the procedure, in this case an example has been chosen where the data of three DST system tests are available. The mathematical model or procedure respectively described in this document can also be applied if only one system test has been performed. The impact of the number of available data from the DST-method on the accuracy will be discussed in the next chapters.

For this system twelve different surface plots are available (4 different storages combined with three different collectors). The aim is to find the surface where the discrepancies between the values of f_{sol} obtained by the DST method and obtained with equation (2.4) are minimal. Thus, for each solar hot water system that has been tested with the DST-method (system number 1, 2 and 6) 12 different values of the solar fraction ($f_{sol,calc}$) have to be calculated. These values are compared with the f_{sol} -values that have been derived from the DST measurements.

In Figure 4.1 a comparison between measured and calculated solar fractions can be seen for one possible combination of the influence parameters. Grey points mark the values $f_{sol,calc}$ which are calculated with equation (2.4), the black points mark the values of $f_{sol,measured}$ that are obtained from measurements according to the DST-method.

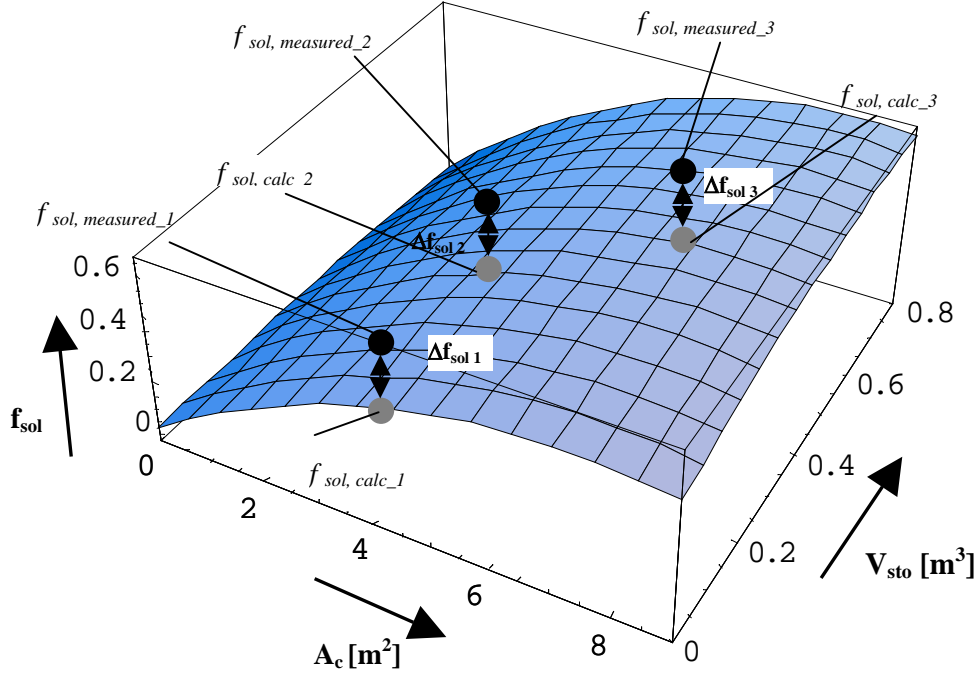


Figure 4.1: Comparison of calculated and measured f_{sol} values

The differences $\Delta f_{sol, i, j}$ between measured and calculated values is calculated with equation 4.1,

$$\Delta f_{sol, i, j} = f_{sol, measured, i} - f_{sol, calc, i, j} \quad (4.1)$$

$i = 1 \dots 3$ System number

$j = 1 \dots 12$ Surface number

The total difference ΔF_{sol} is defined as the summation over the differences $\Delta f_{sol, i}$

$$\Delta F_{sol, j} = \sum_i |\Delta f_{sol, i, j}| \quad 4.2$$

It is assumed that the surface where the value of ΔF_{sol} is minimal describes the system behaviour in the best way. This function will then be used to compute the solar fraction for the remaining systems 3, 4 and 5. Table 4.3 lists the results determined by the mathematical model of the solar fractions of systems 3, 4 and 5. The surface that describes the product line of the hot water system best has the parameters listed in Table 4.2

Table 4.2 Parameters determined for the description of the solar fractions of the product family

$$\begin{array}{ll}
 a1 = & -0.0077 \\
 a2 = & -0.1215 \\
 a3 = & 0.08129 \\
 a4 = & 0.11147 \\
 a5 = & -0.11793 \\
 a6 = & 0.39035 \\
 a7 = & -0.0032 \\
 a8 = & -0.0382
 \end{array}$$

Table 4.3 Results of the solar fractions obtained by the mathematical model

System no.	Amount of collector modules	Collector aperture area [m ²]	Storage tank capacity [m ³]	fsol [-]
1	1	2.0	0.3	0.572
2	2	4.0	0.3	0.725
3	3	6.0	0.3	0.828
4	1	2.0	0.5	0.549
5	2	4.0	0.5	0.723
6	3	6.0	0.5	0.830

5. Error estimation of the mathematical model

In this chapter the errors resulting from the mathematical model as the key element of the developed procedure for the determination of the performance test results of solar domestic hot water systems based on tests of only one or two system are estimated.

In general the total error is comprised of four main errors:

1. Error of the results determined by the DST-Test
2. Error of the TRNSYS simulation
3. Error in fitting the curve to the results of the TRNSYS simulation
4. Error in the selection of the best fitting surface

Error of the results determined by the DST-Test

From previous experience it can be assumed that the DST-test has an uncertainty of approximately +/- 5%¹

Error of the TRNSYS - Simulation

A simulation can only be used as an approach for reflecting the reality. Assumptions and simplification have to be made to reduce the complexity of the physical model to a manageable level that can be described by a mathematical model. There is such a wide range of influence parameters e.g. weather data, collector model and storage model that influence the simulation that the TRNSYS model can only be an approximation to the real behaviour. Hence it is not possible to give reliable figures for the uncertainty of the TRNSYS simulation

Error estimation of fitting the curve to the results of the TRNSYS simulation

It was assumed that the values of the thermal behavior of the system can be described as a function of 2nd order of the storage volume and collector area. The relative discrepancy (cf. chapter 2) between the calculated values and the values obtained with the TRNSYS simulation reaches values up to $\varepsilon_{rel} = 5.5\%$ (for thermosiphon systems that have been modelled with TRNSYS up to now). The maximal absolute error defined with,

$$\varepsilon_{abs} = \left| f_{sol_TRNSYS} - f_{sol_calc} \right|$$

is $\varepsilon_{abs} = 3.0\%$.

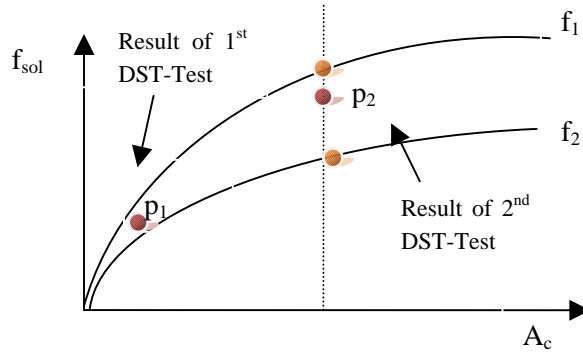
¹ Bridging the gap: Research and Experimental Validation on the DST Performance Test Method for solar Domestic Water Heaters, Final Report, Contract No. SMT4-CT96-2067

Error in the selection of the best fitting surface

As explained in chapter 4 the best fitting surface is defined as the surface where the discrepancy between the solar fractions obtained with the DST-test and the surface described with the mathematical model is minimal. The error that might result from this procedure is illustrated in Figure 5.1 below. The red point p_1 is a value of the solar fraction obtained with the DST-test. The two curves describe two possible functions $f_{sol,1/2} = f(A_c, V_{sto})$ in dependency of the collector aperture area. As it can be seen the red point lies in between the two curves and both functions f_1 and f_2 that are a good approximation for the specific value of f_{sol} . As the point lies marginally closer to the curve described with function f_1 the program defines the surface related to this function as the best fitting surface. For the extrapolation of the test results we will obtain values of solar fractions that lie on the curve f_1 .

If the result of a second DST test is available the following can be assumed:

A second DST-test with a greater collector area gives a value of the solar fraction described by the red point p_2 that lies close to the curve described by the function f_2 . With the 2nd DST-test it can now be stated that the function f_1 is a better approximation of the system behavior than the function f_2 . In chapter 8 the error resulting from this effect will be analyzed in more detail.



5.1: Graphical interpretation of the error arising from fitting DST-results to a surface described by a polynomial of 2nd order

6. Integrating the mathematical model in a computer program

In order to reduce the time necessary to identify the best fitting surface the mathematical model has been integrated in a computer program (Microsoft Excel). The name of the program is DHWScale.. As an example a screenshot of the user-surface is shown in Figure 6.1:

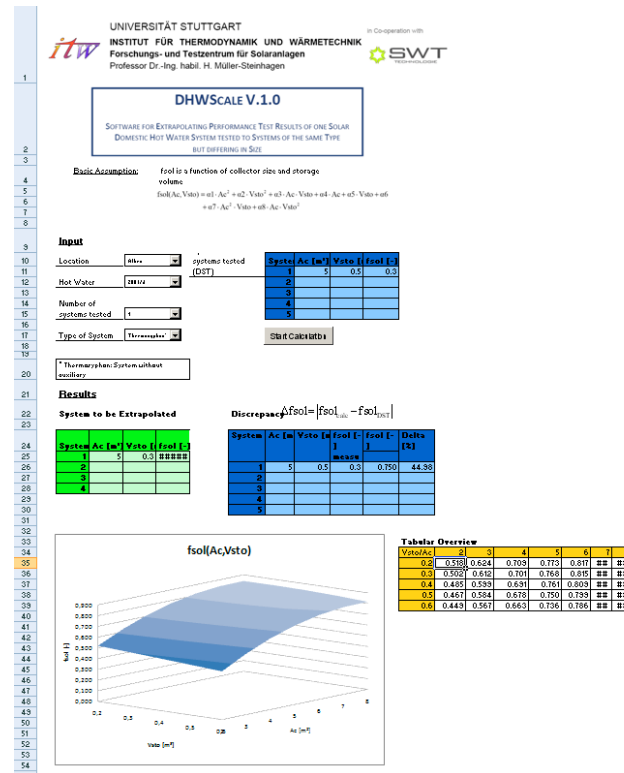


Figure 6.1: Screenshot of the DHWScale –Program

For the solar domestic hot water system(s) of the product line that have/has been tested with the DST-method the following inputs have to be entered in the Excel sheet:

- For each system tested of the product line
 - Collector area
 - Storage tank volume
 - Solar fraction f_{sol}
- Number of systems tested from the product line
- Location (only Athens available up to now)
- Daily hot water consumption

With these data the program automatically computes the best fitting surface for the specific location and hot water consumption. When the surface is known the solar fraction can be computed for arbitrary sizes of collector area and storage tank volume.

In order to have information about the quality of the surface plot the average relative discrepancy between the value of the solar fraction entered in the table (obtained by the DST-method) and the solar fraction obtained with the program calculated will be displayed. The average relative discrepancy is defined with,

$$\bar{\varepsilon}_j^* = \frac{\sum_i^n \frac{|\Delta f_{sol,i,j}|}{f_{sol,i,measured}}}{n} \quad (6.1)$$

7. Specifications of the parameters

In this chapter the influence parameters, which are used to classify the solar hot water systems, are described in more detail.

Thermal collectors

The intention is to identify three different types of thermal collectors which cover a wide range of collectors on the market. Therefore, collectors have been chosen that differ in their thermal performance. The instantaneous efficiency curve of the three solar thermal collectors chosen for the parameter variation can be seen in figures 5.1, 5.2 and 5.3.

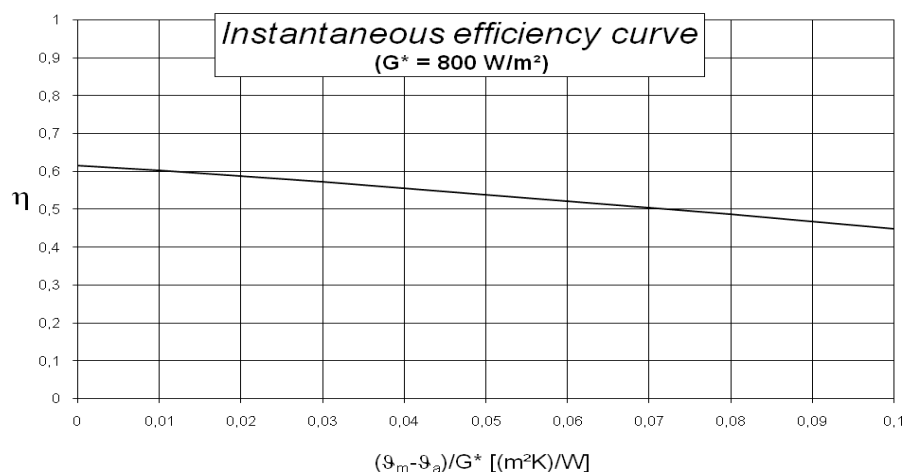


Figure 7.1 Evacuated tube collector

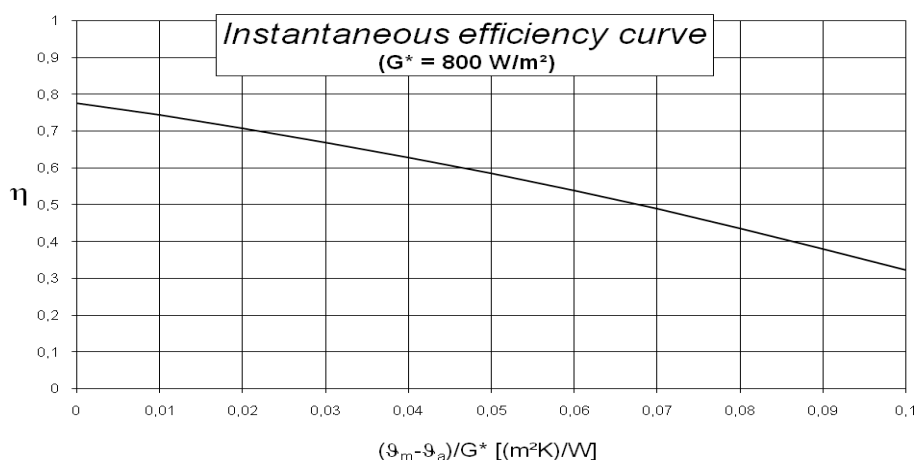


Figure 7.2 Flat plate collector 1

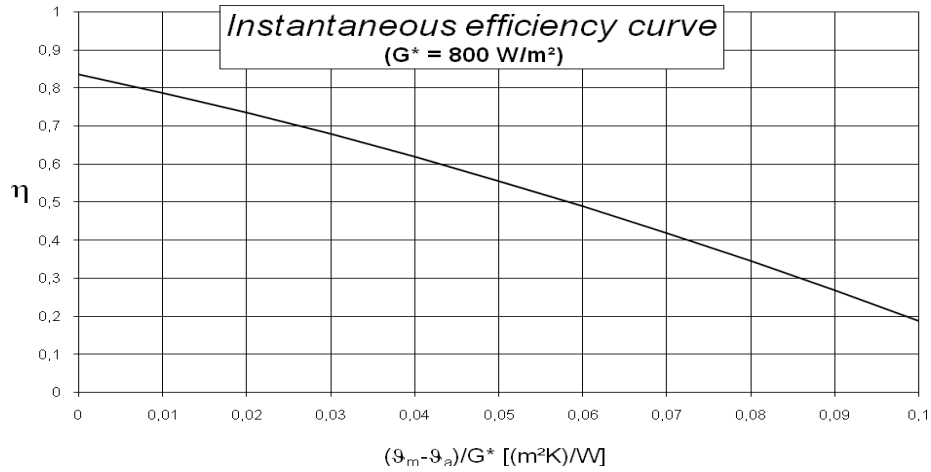


Figure 7.3 Flat plate collector 2

The thermal performance of a solar thermal collector can be described with equation 7.1,

$$\eta = \eta_0 - a_1 \frac{g_m - g_a}{G^*} - a_2 \frac{(g_m - g_a)^2}{G^*} \quad 7.1$$

The coefficients η_0 , a_1 and a_2 of the collectors used here are listed in Table 7.1.

Table 7.1 Parameters of the solar collectors

Collector	η_0	a_1 [W/(m ² K)]	a_2 [W/(m ² K ²)]
Vacuum tube collector	0.616	1.391	0.0037
Flat plate coll. 1	0.775	3.084	0.018
Flat plate coll. 2	0.836	4.726	0.022

Storage

The storage tanks vary in their specific heat loss rate. The heat loss rate depends, among others, on the storage tank volume and the quality of the thermal insulation and can be calculated as follows:

$$(Ua)_0^* = 0.16 \cdot \sqrt{V_{sto} \cdot 1000} \frac{1}{m} \quad (7.2)$$

$$(Ua)_0 = (Ua)_0^* \cdot \beta$$

The parameter β takes the quality of the thermal insulation into account and has the following values:

$$\beta = [0.7, 0.85, 1.0, 1.2]$$

8. Validation of the mathematical model

For the validation of the mathematical model developed the results of the DST tests of one thermosiphon system product family are used. Systems of this product family with different collector area and store volume were tested according to the DST method at the three laboratories CSTB, INETI and ITW. The results obtained from these tests will be compared with the results that are obtained by the mathematical model. Based on the DST-test the following results for the location of Athens and a hot water demand of 200 l/d were determined.

8.1: DST-results ($f_{\text{sol,DST}}$) obtained by the three laboratories CSTB, INETI and ITW

Number	A_c	V_{sto}	$f_{\text{sol,DST}}$
1	3.48	0.18	0.74
2	5.22	0.30	0.82
3	3.96	0.18	0.72
4	3.96	0.15	0.70
5	3.96	0.30	0.75
6	1.86	0.30	0.61
7	3.72	0.30	0.77
8	5.58	0.3	0.82

For one system configuration (collector area: 1.74 m², store volume: 0.15 m³) the solar fraction is not available for a hot water demand of 200 l/d so that only eight system configurations remain.

With the mathematical model the results depicted in the table 8.2 are gained. The parameters of the system that have been entered in the program as “system tested” is defined in the line: “System tested with DST”. With the values of A_c , V_{sto} and $f_{\text{sol,DST}}$ the best fitting surface was selected by the program and the values of $f_{\text{sol,calc}}$ are calculated by the mathematical model for the different systems of the product line. In addition, the discrepancy between the calculated values of the solar fraction and the solar fractions obtained by the DST-method ($\Delta = f_{\text{sol,DST}} - f_{\text{sol,calc}}$) and the relative error (ε_{rel}) between both is displayed for each trial. The following three trials have been performed:

In the first trial (Trial 1) a thermosiphon system with $A_c = 3.48$ and $V_{\text{sto}} = 0.18$ (System no. 1) has been tested with the DST-method and a solar fraction of $f_{\text{sol,DST}} = 0.74$ has been obtained. These values are now entered in the DHWScale-program to extrapolate the results to systems of the same product family but different in size (Note: The input value for f_{sol} is printed in Table 8.2, in the row “Input value”, column “Trial 1” in bold). The program calculates the solar fraction to $f_{\text{sol}} = 0.714$. For the systems 2 to 7 of the same product line the values of f_{sol} can be found in the row “Trial 1, $f_{\text{sol,calc1}}$ ”.

In a second trial a thermosiphon system with $A_c = 3.96$ and $V_{\text{sto}} = 0.18$ (System no. 4) has been tested with the DST-method and a solar fraction of $f_{\text{sol,DST}} = 0.70$ has been obtained. Again, these values are entered in the DHWScale program. (Note: The input value for f_{sol} is printed in Table 8.2, in the row “Input value”, column “Trial 2” in bold). The results obtained for the other systems of the product line by means of extrapolation are listed in the row “Trial 2, $f_{\text{sol,calc1}}$ ”.

For the third trial it is assumed that two thermosiphon systems (system 3 and system 7) have been tested with a DST-test. Both systems have been entered into the program as input data to obtain the solar fractions for the 5 remaining systems of the product family.

8.2: Comparison of the DST-results and the results from the mathematical model

No	A_c	V_{sto}	$f_{sol,DST}$	Trial 1		Trial 2		Trial 3	
				$f_{sol,calc,1}$	$\Delta / (\varepsilon_{rel})$ [%]	$f_{sol,calc,2}$	$\Delta / (\varepsilon_{rel})$ [%]	$f_{sol,calc,3}$	$\Delta / (\varepsilon_{rel})$ [%]
	System tested with DST Input value			1 0.74		4 0.70		1;4 0.74; 0.77	
1	3.48	0.18	0.74	0.714	2.6 (3.5)	0.680	6.0 (8.1)	0.703	3.7 (5.0)
2	5.22	0.30	0.82	0.816	0.4 (0.5)	0.777	4.3 (5.2)	0.803	1.7 (2.1)
3	3.96	0.18	0.72	0.744	2.4 (3.3)	0.708	1.2 (1.7)	0.731	1.1 (1.5)
4	3.96	0.15	0.70	0.741	4.1 (5.9)	0.705	0.5 (0.7)	0.727	2.7 (3.9)
5	3.96	0.30	0.75	0.750	0.0 (0.0)	0.713	3.7 (4.9)	0.742	0.8 (1.1)
6	1.86	0.30	0.61	0.582	2.8 (4.6)	0.550	6.0 (9.8)	0.583	2.7 (4.4)
7	3.72	0.30	0.77	0.735	3.5 (4.5)	0.688	8.2 (10.6)	0.727	4.3 (5.6)
8	5.58	0.3	0.82	0.830	1.0 (1.2)	0.791	2.9 (3.7)	0.816	0.4 (0.5)

The relative error between the results obtained for f_{sol} from the DST test and the calculation procedure is calculated by the following equation 8.1.,

$$\varepsilon = \left| \frac{f_{sol_DST} - f_{sol_calc}}{f_{sol_DST}} \right| \cdot 100\% \quad (8.1)$$

As can be seen from table 8.2 the maximum relative error for Trial 1 is 5.9 % and 10.6 % for the second trial and 5.6 % for the third trial. The mean error, defined with

$$\varepsilon_{mean} = \frac{\varepsilon_1 + \varepsilon_2 + \dots + \varepsilon_8}{8} \quad (8.2)$$

is 2.25 % (Trial 1), 5.9 % (Trial 2) and 3.0 % (Trial3).

For the other hot water demands of 110 l/d and 300 l/d comparable results are obtained.

9. Discussion of the model

Based on one or more physical system tests the solar fractions of solar domestic hot water systems of the same product family can be estimated for arbitrary collector sizes and storage volumes by means of the extrapolation procedure described in this document. In this chapter the practicability of the calculation model as the key element of the extrapolation procedure will be analysed.

So far, the program has only been validated with one product family. The comparison of the program with the DST-test performed by the three laboratories showed a good agreement. The uncertainty of the program lies in the range of 11 % if one system test is performed but can be further reduced if more than one system of the same product line is tested. However, for a more detailed analysis of the extrapolation procedure further DST-tests should be performed on different product families to compare the results for a wider range of systems.

The same is valid with regard to the performance test method. Up to now the extrapolation procedure was only validated for one product line of thermosiphon solar domestic hot water systems tested with the DST method according to ISO 9495-2. In principle it can be expected that the extrapolation method can also be applied on results obtained by CSTG tests according to ISO 9495-2. However a reliable statement can only be made after a corresponding validation is carried out

The developed extrapolation procedure has the advantage that it can be easily extended to take additional system parameters into account. In future it might be desirable to have this tool available not only for the location of Athens, but also for other regions. It might also be necessary to add more choices for daily hot water loads. The extension of the procedure implies a high number of further simulations but the same mathematical model as described in this report can be used.

In general the program can also be used to extrapolate performance test results of other types of DHW systems such as forced circulation systems with or without auxiliary heating, thermosiphon systems with auxiliary heating or in principle even combisystems. For forced circulation systems with and without auxiliary heating, first simulations have already been performed and promising results have been obtained. For a validation of these results, system tests of product families have to be carried out similar to those of the thermosiphon systems. Additionally, due to the higher complexity of these systems with more system parameters that influence the thermal performance, a higher number of simulations have to be carried out to take into account the wide range of systems available on the market.

10. Summary

An extrapolation procedure including a mathematical model has been developed which can be used for the determination of the solar fraction of systems being part of a product line by means of an extrapolation procedure using input values of only one or a few systems physically tested. The developed procedure has been implemented in an EXCEL based software tool named DHWScale.

As the model is described by a second order polynomial results can be obtained within seconds. The mathematical model has the advantage that only a few system tests are necessary to determine the solar fraction for a whole product family. This approach offers the possibility to reduce the time and cost necessary to obtain Solar Keymark certification of solar domestic hot water systems. The validation of the program with one thermosiphon product family tested by DST showed good results. Depending on the accuracy desired already one system test is sufficient (relative error of about 11 %) or at least two system tests have to be performed (relative error about 6 %). However, up to now only the DST-results of one product family were available. For a more profound assessment of the developed procedure more product families have to be tested with the DST-method.

In principle it is possible to extend the DHWScale program towards other system designs such as forced circulated DHW systems with or without auxiliary heating or combisystems. First experiences have been gained with forced circulated DHW systems but a validation is necessary before a statement about the accuracy of the results obtained can be made. It is also expected that for these other types of systems further parameters have to be taken into account such as e.g. the influence of the auxiliary volume. This implies a huge number of additional TRNSYS simulations.

The DHWScale program is a first approach for the determination of system test results by means of an extrapolation procedure. In principle the methodology of this approach can be extended to additional parameters (e.g. locations, loads) and system concepts. In order to gain information about the practicability of this approach and the EXCEL tool, feedback from testing laboratories, industry and certifiers is desired.

Annex A



FORSCHUNGS- UND TESTZENTRUM FÜR SOLARANLAGEN

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Professor Dr. Dr.-Ing. habil. H. Müller-Steinhagen

in Kooperation mit



MANUAL FOR THE SOFTWARE TOOL DHWSCALE

Software for Extrapolating Performance Test Results of one Solar
Domestic Hot Water System tested to Systems of the same Type but
differing in Size

Version Number: 01

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Introduction

This software can be used to extrapolate performance test results of a Solar Domestic Hot Water System (DHW system) obtained with the DST-method to other DHW systems of the same product line. The software is based upon the assumption that within a product line the solar fraction f_{sol} is a function of the collector area and store volume only. The equation used for the mathematical description of this assumption is as follows:

$$f_{sol}(Ac, V_{sto}) = a1 \cdot Ac^2 + a2 \cdot V_{sto}^2 + a3 \cdot Ac \cdot V_{sto} + a4 \cdot Ac + a5 \cdot V_{sto} + a6 + a7 \cdot Ac^2 \cdot V_{sto} + a8 \cdot Ac \cdot V_{sto}^2$$

The parameters $a1 \dots a8$ have been previously calculated with the simulation program TRNSYS for a thermosiphon system at the location of Athens. Further information about the mathematical model of this tool can be obtained from [1].

Using the software

General

The calculation software is based on Microsoft EXCEL and therefore it is required that EXCEL is installed. The software has been developed with Microsoft EXCEL 2003 but is also running under Microsoft EXCEL 2000.

In order to run the tool you have to set the macro security of EXCEL to low. After starting the calculation tool the spreadsheet named "user" appears. This is the only folder the user has to work with.

Input Data

The following parameters have to be entered by the user in the section named "Input":

1. **Hot Water Demand:** Choose one of the following hot water demands: 110 l/d, 200 l/d or 300 l/d
2. **Number of Systems Tested:** Enter the number of systems tested with the DST-test. All the systems have to belong to the same product line. For each system tested fill out one line in the table "**Specification of the System tested (DST)**"

3. **Specification of the system:** In this table you have to enter the information of the system you have tested with the DST-Method. The important values are the aperture collector area (A_c), the store volume (V_{sto}) calculated from the thermal heat capacity of the store determined by the DST test as well as the solar fraction resulting from the annual system simulation performed for the corresponding boundary conditions.

It is important that the number of systems you define in the table match the number of systems you define as input data in "**number of systems tested**".

You can now start the calculation by clicking the button "**Start Calculation**".

Results:

If the calculation was successful you will find the following information in the section "**Results**":

- **Parameter specification:** In this table you will find the values of $a_1 \dots a_8$ describing the equation

$$f_{sol}(A_c, V_{sto}) = a_1 \cdot A_c^2 + a_2 \cdot V_{sto}^2 + a_3 \cdot A_c \cdot V_{sto} + a_4 \cdot A_c + a_5 \cdot V_{sto} + a_6 + a_7 \cdot A_c^2 \cdot V_{sto} + a_8 \cdot A_c \cdot V_{sto}^2$$

- **Discrepancy:** In this table, in the column named "**Delta**", the discrepancy between the value of f_{sol} calculated with this tool and the value of f_{sol} obtained with the DST-test is listed (absolute value in %). You will also find the value of the DST-test you have entered (column $f_{sol, \text{measured}}$) and the value of f_{sol} calculated with this tool
- **System to be extrapolated:** Here you can specify the system for that you want to determine f_{sol} based on an extrapolation and/or interpolation from the DST-test results. The system has to be defined by entering the collector area (A_c) and the storage volume (V_{sto}). With the equation described above f_{sol} will be computed automatically. Please note, that the tool has been developed for small to medium size DHW-systems. You can only extrapolate the results within a certain range. For realistic results the collector area has to be in the range of 2...8 m² and the storage volume in the range of 0.2...0.6 m³.

- **Tabular Overview:** In this table values of f_{sol} are displayed over a wide range of collector area sizes and storage volumes for further DHW systems of the same product line as the system tested. The figure next to the table illustrates the system behaviour in dependency of the collector area and storage volume.

For further questions or any remarks, please contact the persons mentioned at the cover page.

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