Testing of solar hot water stores by means of up- and down-scaling algorithms

H. Drück, S. Bachmann, H. Müller-Steinhagen
University of Stuttgart, Institute for Thermodynamics and Thermal Engineering (ITW)
Pfaffenwaldring 6, 70550 Stuttgart, Germany
Tel.: +49 711/685-63536, Fax: +49 711/685-63503
email: drueck@itw.uni-stuttgart.de

Abstract

For the characterisation of the thermal behaviour of a heat store in conjunction with a numerical store model it is necessary that the appropriate modelling parameters are known. According to the present version of ENV 12977-3 (Thermal solar systems and components - Custom built systems - Part 3: Performance characterisation of stores for solar heating systems) it is required that every store has to be tested in order to determine its parameters. This is even the case, if the stores belong to a series with identical design and only vary in size or volume, or with regard to the heat exchangers. In order to reduce costs for testing, it is favourable if store parameters within one store series can be determined from measurements of certain stores from the same series. In order to develop such a procedure, appropriate investigations have been carried out. Therefore several hot water store series of different manufacturers were tested and their parameters were determined by means of parameter identification. Afterwards, algorithms have been developed for calculating certain store parameters based on the parameters of larger or smaller stores with identical basic design. In order to verify these algorithms, yearly simulations with the simulation program TRNSYS were carried out using the parameters obtained by testing the store on one hand, and on the other hand using the parameters determined by up- and downscaling, in order to determine the fractional energy savings.
Investigations carried out so far show that it is generally possible to calculate parameters of single stores being part of a series of stores based on test results for selected stores. Furthermore, the simulations showed that the deviation between the fractional energy savings determined on the basis of the measured and the calculated store parameters is negligible. In general, the developed up- and down scaling approach is a promising way to achieve a significant reduction of the costs for testing systems and stores, respectively.
This paper describes the algorithms developed for the calculation of the store parameters by means of up- and downscaling. Furthermore the limitations of the method as well as the reliability of the results will be discussed.

Keywords: Hot water stores, store testing, standardisation, ENV 12977-3, up- and downscaling

1. Introduction

For the description of the thermal behaviour of a heat store in combination with a numerical store model it is necessary to know the parameters of the store such as the volume, the heat loss rate and the heat transfer capacity rate of immersed heat exchangers. According to the present version of the European standard ENV 12977-3 it is required that every store has to be tested in order to determine its parameters. This is even the case, if the stores only vary in volume and with regard to the heat exchangers. In order to reduce costs for testing it was examined if store parameters can be calculated within one store series based on measurements of certain stores out of this series. These investigations were carried out in the context of the EuroSol-Project, which is a national project of the Institute for Thermodynamics and Thermal Engineering (ITW) together with German solar industry and co-financed by the DBU (Deutsche Bundesstiftung Umwelt).

Several store series from different manufacturers were tested and their parameters were determined by means of parameter identification. Afterwards algorithms were developed to calculate certain store parameters based on the parameters of larger or smaller stores which are identical in design; this approach is named up- and downscaling.

2. Examined stores

To-date four series of hot water stores have been examined. Figure 1 shows the schematic set-up of **store series B**: This series consists of 3 hot water stores with a nominal volume of 300 litres, 400 litres and 500 litres with immersed heat exchangers for solar charging and auxiliary charging. The solar loop heat exchanger is equipped with a special device for stratified charging. All stores of this series are thermally insulated with an uniform isolation made of polyurethane foam.

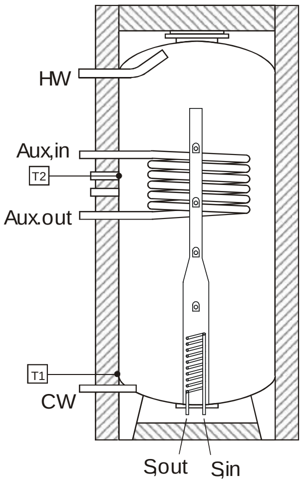

Figure 1: Store series B

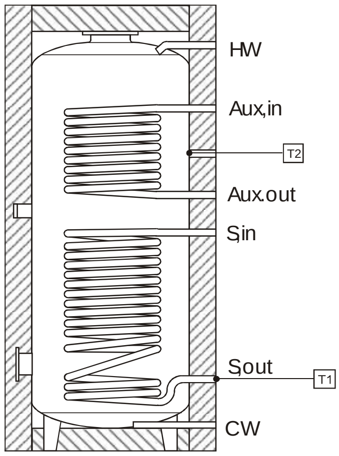

Figure 2: Store series V

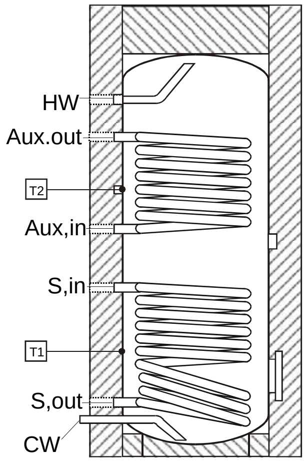

Figure 3: Store series W

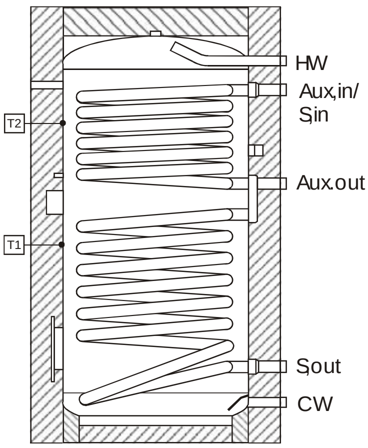

Figure 4: Store series P

Figure 2 shows the schematic set-up of **store series V**: This store series consists of 3 hot water stores with a nominal volume of 300 litres, 400 litres and 500 litres with immersed heat exchangers for solar charging and auxiliary charging. All stores of this series are equipped with different materials for thermal insulation such as hard and soft polyurethane foam.

Figure 3 shows the schematic set-up of **store series W**: This series also consists of 3 stores with a nominal volume of 300 litres, 400 litres and 500 litres with immersed heat exchangers for solar and auxiliary charging. All stores of this series are equipped with a uniform isolation of polyurethane foam.

Figure 4 shows the schematic set-up of **store series P**: This store series consists of 3 hot water stores with a nominal volume of 290 litres, 390 litres and 490 litres with immersed heat exchangers for solar and auxiliary charging. All stores of this series are equipped with a uniform isolation of polystyrene.

Legend for figure 1-4:

CW	Cold water inlet	S,in	from solar collector	Aux,in	from auxiliary heater
HW	Hot water outlet	S,out	to solar collector	Aux,out	to auxiliary heater

3. Store parameters

Table 1 gives an overview about the most important store parameters used in TRNSYS Type 140 (MULTIPORT Store model [1]).

Table 1: Store parameters

Parameter:	Description:
H_s [m]	Height of store
V_s [l]	Volume of store (without heat exchangers)
V_{hx} [l]	Volume of heat exchangers
λ_{eff} [W/(m·K)]	Effective vertical thermal conductivity of store
$(UA)_{s,a}$ [W/K]	Heat loss rate of store
K_{WT} [W/K]	Constant for describing the heat transfer capacity rate
b_{h1} [-]	Parameter describing the dependence of heat transfer capacity rate on the mass flow rate through the heat exchanger
b_{h3} [-]	Parameter describing the dependence of heat transfer capacity rate on the temperature level
n [-]	Stratification number
z_x [-]	Relative height of connections or temperature sensors of store

4. Procedures for calculation of the store parameters by means of up- and downscaling

4.1 Heat loss rate

The heat loss rate can be calculated by equation (1). The structure of this equation in principle follows the approach used in ENV 12977-1.

$$(UA)_{s,a} = a \cdot \sqrt{V} \tag{1}$$

with $(UA)_{s,a}$ = heat loss rate of the store [W/K]
V = volume of the whole store[litres]
a = constant (representative for a store series) [W/(Km^{0,5})]

Procedure:
If the heat loss rate and the volume of the largest store of a series are known, the constant “a” can be calculated by equation (1). For smaller stores of this store series the heat loss rate can than be calculated by equation 1 if the volume of the smaller stores is known.

4.2 Heat exchangers

The heat transfer capacity rate $(UA)_{hx}$ of the immersed heat exchangers is described with the following equation:

$$(UA)_{hx} = K_{WT} \cdot \dot{m}_{hx}^{b_{h1}} \cdot \left[\vartheta_{hx,in} - \vartheta_{s,i}\right]^{b_{h2}} \cdot \left[\frac{\vartheta_{hx,in} + \vartheta_{s,i}}{2}\right]^{b_{h3}} \tag{2}$$

with: K_{WT} = constant for description of the heat transfer capacity rate [W/K]

$\dot{m}_{hx}$ = mass flow rate through the heat exchanger [kg/s]
$\vartheta_{hx,in}$ = inlet temperature of the heat exchanger [°C]
$\vartheta_{s,i}$ = temperature of the corresponding store tank node i in the numerical model [°C]
b_{h1} = parameter describing the dependence of heat transfer capacity rate on the mass flow rate through heat exchanger (hx) [-]
b_{h2} = parameter describing the dependence of heat transfer capacity rate on the temperature difference between hx and store (here neglected, b_{h2} = 0) [-]
b_{h3} = parameter describing the dependence of heat transfer capacity rate on the temperature level [-]

For the heat exchangers of the store that was not tested, the heat transfer capacity rate $(UA)_{hx}$ is calculated based on the assumption that $(UA)_{hx}$ is directly related to the area of the heat exchanger. In order to perform the interpolation for the calculation of $(UA)_{hx}$ of the heat exchangers of a medium size store it is necessary that $(UA)_{hx}$ of the heat exchangers of the smallest and largest store of the series was determined on the basis of measurements. Since $(UA)_{hx}$ usually depends on the temperature level and the mass flow rate through the heat exchanger the calculation of $(UA)_{hx}$ for the heat exchangers of the medium size store requires the determination of the corresponding parameters K_{WT}, b_{h1} and b_{h3} in the following way:

1. Calculation of some values of $(UA)_{hx}$ for different mass flow rates and temperatures for the heat exchangers of the smallest and the largest store.
2. Calculation of the appropriate values of $(UA)_{hx}$ for the heat exchanger of the medium size store by linear interpolation of the values of the heat exchanger for the smallest and largest store according to the areas of the heat exchangers.
3. Determination of the parameters K_{WT}, b_{h1} and b_{h3} for the heat exchanger of the medium size store by regression of these values based on equation 2.

4.3 Volume

The volume of the store and the immersed heat exchangers has to be used according to the manufacturer's information. The height of the store H_s can be calculated with the store volume and the diameter of the store (also based on manufacturer's information) for a cylindrical geometry.

4.4 Relative heights of connections and temperature sensors

These parameters are calculated based on the design drawing and the determined store height H_s.

4.5 Effective vertical thermal conductivity of the store

The effective vertical thermal conductivity λ_{eff} is a quantity for the description of the heat transfer from the top of the store to the bottom. It is a lumped parameter that takes into account the heat conduction in the wall of the store, in the water, in the internals (e.g. heat exchangers) of the store as well as convection flows inside the store. The investigations on the four store series showed that the values within one store series vary slightly only. Since these differences influence the thermal behaviour of the store only in a minor way, it is possible to use one default value for all stores of a series.

4.6 Stratification number

The stratification number "n" is a quantity for the description of the temperature stratification during direct discharge of the store. If a numerical store model based on a finite-difference-approach is used, the stratification number directly corresponds to the number of nodes used in the numerical model. If the stratification number is relatively high (n > 30) it is only a secondary parameter with regard to the influence on the fractional energy savings. Due to the fact that the stratification numbers of the stores under investigation are relatively high, it is not necessary to calculate the stratification numbers of the stores that were not tested. Instead of this, a default value of 100 can be used.

5. Results

In order to verify the up- and downscaling methods described in chapter 4 simulation studies were carried out. For that purpose it was assumed that the largest store of a store series was completely tested according to ENV 12977-3. Furthermore it was assumed that the heat transfer capacity rates of the immersed heat exchangers of the smallest store were also determined by measurements. Based on these results the parameters for the medium-sized store were calculated according to the procedures described in chapter 4.

In the following table 4 the column "measured" shows the store parameters gained from a test according to ENV 12977-3 and the column "calculated" shows the parameters for the medium-sized store of series W that were determined without any testing of this store based on calculations or the information provided by the manufacturer. Additionally the values for the fractional energy savings f_{sav} were determined based on annual simulations for a reference solar thermal system by using the individual store parameters.

Table 4: Comparison of store parameters and simulation results for store series W:

	300 litre	400 litre		500 litre
parameter	measured	measured	calculated	measured
V_s [l]	322	405	391	503
H_s [m]	1,43	1,51	1,44	1,60
λ_{eff} [W/(m·K)]	1,81	1,87	1,90	1,90
$(UA)_{s,a}$ norm. [-]	0,79	0,88	0,90	1,0
$V_{hx,sol}$ [l]	8,3	10,2	10,0	12,8
K_{sol} [W/K]	135,8	147,2	143,5	148,9
$b_{h1,sol}$ [-]	0,205	0,234	0,243	0,266
$b_{h3,sol}$ [-]	0,472	0,511	0,514	0,538
n [-]	108	167	174	174
$V_{hx,aux}$ [l]	6,0	6,9	7,0	9,0
K_{aux} [W/K]	139,7	120,8	132,0	129,2
$b_{h1,aux}$ [-]	0,255	0,285	0,263	0,267
$b_{h3,aux}$ [-]	0,413	0,493	0,455	0,473
$z_{sol,in}$ [-]	0,43	0,42	0,43	0,51
$z_{sol,out}$ [-]	0,0	0,0	0,0	0,0

$Z_{aux,in}$ [-]	0,59	0,61	0,64	0,58
$Z_{aux,out}$ [-]	0,85	0,85	0,88	0,86
z_{CW} [-]	0,0	0,0	0,0	0,0
z_{HW} [-]	1,0	1,0	1,0	1,0
z_{Tsol} [-]	0,09	0,10	0,12	0,09
z_{Taux} [-]	0,70	0,72	0,76	0,71
f_{sav} [%]	63,0	73,7	73,5	77,5

Table 4 shows a very good agreement for the fractional energy savings determined for the medium-sized store on the basis of both parameter sets. In addition, the results obtained for the store series B, V and P were quite promising. This shows, that the procedures for the calculation of the store parameters by means of up- and downscaling as described in chapter 4 are adequate and deliver reliable results.

6. Conclusion

Based on the investigations carried out so far, the following conclusions can be drawn concerning the determination of store parameters for a series of stores based on up- and down-scaling procedures:

- it is possible to calculate the heat loss rate for a series of stores based on measurements of only one store out of the store series
- the heat transfer capacity rate of immersed heat exchangers can be calculated based on measurements of 2 stores out of a store series
- concerning the effective vertical thermal conductivity and the stratification number it is possible to use the values of the largest tested store for all stores of the store series

Finally it can be stated that the examinations carried out so far show that it is in general possible to calculate parameters of stores being part of a series of stores, based on test results of certain stores. Furthermore, the simulations showed that the deviation of the fractional energy savings determined on the basis of the measured and calculated store parameters is neglectable.

The up- and down scaling approach described in this paper is a promising way towards a significant reduction of the costs for testing systems according to the CTSS procedure (CTSS: Component Testing – System Simulation, ENV 12977-2). For a broader validation of the up- and down scaling procedures and in order to gain further experience it is recommended to apply the up- and downscaling procedure on additional store series.

In order to provide a basis for this, the procedure for the "determination of store parameters by means of up-scaling and down-scaling" will be included as an informal annex in the revised version of ENV / EN 12977-3 "Thermal solar systems and components — Custom built systems — Part 3: Performance test methods for solar water heater stores".

References

[1] DRÜCK, H. (2000) MULTIPORT store model for TRNSYS, Type 140, Version 1.99, Institut für Thermodynamik und Wärmetechnik (ITW), Universität Stuttgart, November 2000, Stuttgart, Germany

The above mentioned European standards are available from: Beuth Verlag GmbH, Burggrafenstrasse 6, 10787 Berlin, Germany, Internet: www.beuth.de.