Hot water performance of solar combistores

Description of a test method and the experience gained with the application of the method on three different types of combistores

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Description of a test method and the experience gained with the application of the method on three different types of combistores

by

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A technical report of Subtask B

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1 Introduction

The storage medium used in solar combistores is usually the water of the space heating loop and not the tap water which is used in 'typical' solar domestic hot waters stores. Hence the tap water is warmed up on demand by passing a heat exchanger. This heat exchanger can either be placed inside or outside the tank containing the water of the space heating loop. If the heat exchanger is in direct thermal contact with the storage medium, the maximum tap water temperature at the start of the draw-off can be similar to the temperature of the water inside the store.
The tap water volume inside the heat exchanger can vary in a wide range - from a few litres inside a typical immersed heat exchanger up to several hundred litres for a tank-in-tank store.

In order to compare and assess solar combistores it is, among others, necessary to be able to characterise their performance with regard to hot water preparation. In principle, the following two criteria can be used for this purpose:

- **Constancy of hot water temperature:** The temperature constancy of the water tapped from the storage device can be considered as an indicator for the 'hot water comfort'.
- **Utilised hot water volume:** The utilised hot water volume (V_{uhw}) indicates the amount of hot water that can be tapped from the storage device with the temperature required by the user ($\vartheta_{hw,set}$). Hence, the utilised hot water volume is an indicator for the security of hot water supply.

Within a German project (Kombianlagenprojekt) it was decided to focus only on the utilised hot water volume as the indicator used for the assessment of the hot water performance of solar combistores. The main reason for not taking into account the temperature constancy of the tapped hot water was the problem of the mixing device. This mixer is used to control the hot water temperature by adding cold water to the hot water withdrawn from the store or heat exchanger respectively. Such a mixing device is required for all domestic hot water stores and for some combistores (depending on the concept used for the preparation of hot water). In cases where a mixing device is used, the constancy of the hot water temperature strongly depends on the performance of the mixing device. But unfortunately this mixing device is frequently not an integral part of the solar thermal system delivered by the manufacturer. It is common practice that the mixing device is supplied by the installer. As a result of this the constancy of the hot water temperature depends strongly on the individual combination of store an mixing device. Therefore it is obvious that the temperature constancy is not a suitable indicator for the hot water performance of a combistore itself.

2 Determination of the 'utilised hot water volume'

In this chapter the proposed test sequences and evaluation procedure used for the determination of the utilised hot water volume are described. In order to investigate the dependence of the results on the experimental conditions and the evaluation procedure several approaches are applied. These approaches differing from the proposed procedure are described in italics.
Furthermore the reproducibility of the test results is shown by some repeated tests.

2.1 Description of test sequences

In order to generate a temperature distribution inside the store which is close to reality, the whole store is initially heated to a uniform temperature of 30 °C (conditioned); this ensures that also the lower part of the store is slightly preheated. Afterwards the auxiliary part (for domestic hot water) is charged via the appropriate connections according to the following boundary conditions:

- Charging with a volume flow rate of 350 l/h and a thermal power of 15 kW (±10 %).
  The test sequences presented in this paper were carried out with a thermal power of approximately 18 kW due to the gas boiler used as heat source.
- Charging is stopped when the temperature $\vartheta_{HW,set}$ is reached at the sensor used for controlling the hot water auxiliary heating.
- The value used for $\vartheta_{HW,set}$ is specified by the manufacturer.
- If the temperature at the sensor which is used for controlling the hot water auxiliary heating drops below $\vartheta_{HW,set}$, the auxiliary heating is not re-started. The reason for this is that otherwise the determined 'utilised hot water volume' would strongly depend on the available heating power.

Immediately after charging, the hot water is tapped according to the following boundary conditions:

- Cold water inlet temperature ϑ_{CW}: 15^{o}C ± 2 K
- Discharge of hot water (tap profile):
  - 5 min with 5 l/min = 300 l/h
  - 3 min with 15 l/min = 900 l/h
  - afterwards with 10 l/min = 600 l/h
- The hot water discharge is stopped, when the outlet temperature is continuously below 30 °C.

2.2 Evaluation

In a **first step** the amount of heat ($Q_{HW,meas}$) which is tapped from the store is calculated, based on the temperature difference (ΔT) between cold water inlet and hot water outlet temperature and the volume flow rate integrated over the time until the termination criteria for $Q_{HW,meas}$ is reached.

In a **second step** the utilised hot water volume V_{uhw} is calculated as the amount of water which can be heated from 10 °C to 45 °C with the heat $Q_{HW,meas}$.

In the recommended procedure the calculation of $Q_{HW,meas}$ is stopped, until ΔT is permanently below 30 K. The value of 30 K was chosen based on a cold water inlet temperature ϑ_{CW} of 15 °C (corresponding to the test conditions) and a desired hot water temperature of $\vartheta_{HW,set}$ of 45 °C.

In order to investigate the influence of different termination criteria for the calculation of $Q_{HW,meas}$, the following two approaches were investigated additionally:

- *Termination when ΔT is permanently below 35 K (leads to calculation of $Q_{HW,meas,35}$). The value of 35 K is based on a cold water inlet temperature ϑ_{CW} of 10 °C (corresponding to the average operation conditions) and a desired hot water temperature of $\vartheta_{HW,set}$ of 45 °C.*
- *Termination when the hot water outlet temperature ϑ_{HW} of the store drops permanently below 45 °C (leads to calculation of $Q_{HW,meas,45}$). This approach is based on a desired hot water temperature of ϑ_{HW} of 45 °C.*

Based on $Q_{HW,meas,35}$ and $Q_{HW,meas,45}$ the utilised hot water volumes $V_{uhw,35}$ and $V_{uhw,45}$ are calculated as the amount of hot water which can be heated from 10 °C to 45 °C.

3 The stores investigated

In order to gain experience with the proposed procedure for the determination of the utilised hot water volume (V_{uhw}) this procedure was applied on three different combistores. These stores were selected because they prepare the hot water in three completely different ways:

The first combistore uses an immersed heat exchanger (smooth copper tube) which is mounted on the whole inside surface of the mantle and top of the store (see Figure 1, store A).

In the second store the preparation of hot water is based on a thermosiphonical driven heat exchanger which is mounted in the upper part of the store and is equipped with a kind of stratification device (see Figure 1, store B).

The third one is a so-called tank-in-tank combistore with a conical hot water tank inside, which reaches nearly down to the bottom of the store (see Figure 1, store C).

Table 1 shows the volumes of the stores and the hot water heat exchangers as well as the boundary conditions for charging the hot water auxiliary part (temperature sensor used and switch-off temperature).

Table 1: Volumes of store and hot water heat exchanger and boundary conditions for charging the hot water auxiliary part

store	volume store [litres]	volume hot water heat exchanger [litres]	temperature sensor	switch-off temperature [°C]
A	675	15	T3	55
B	830	10	T2	55
C	755	228	T3	55

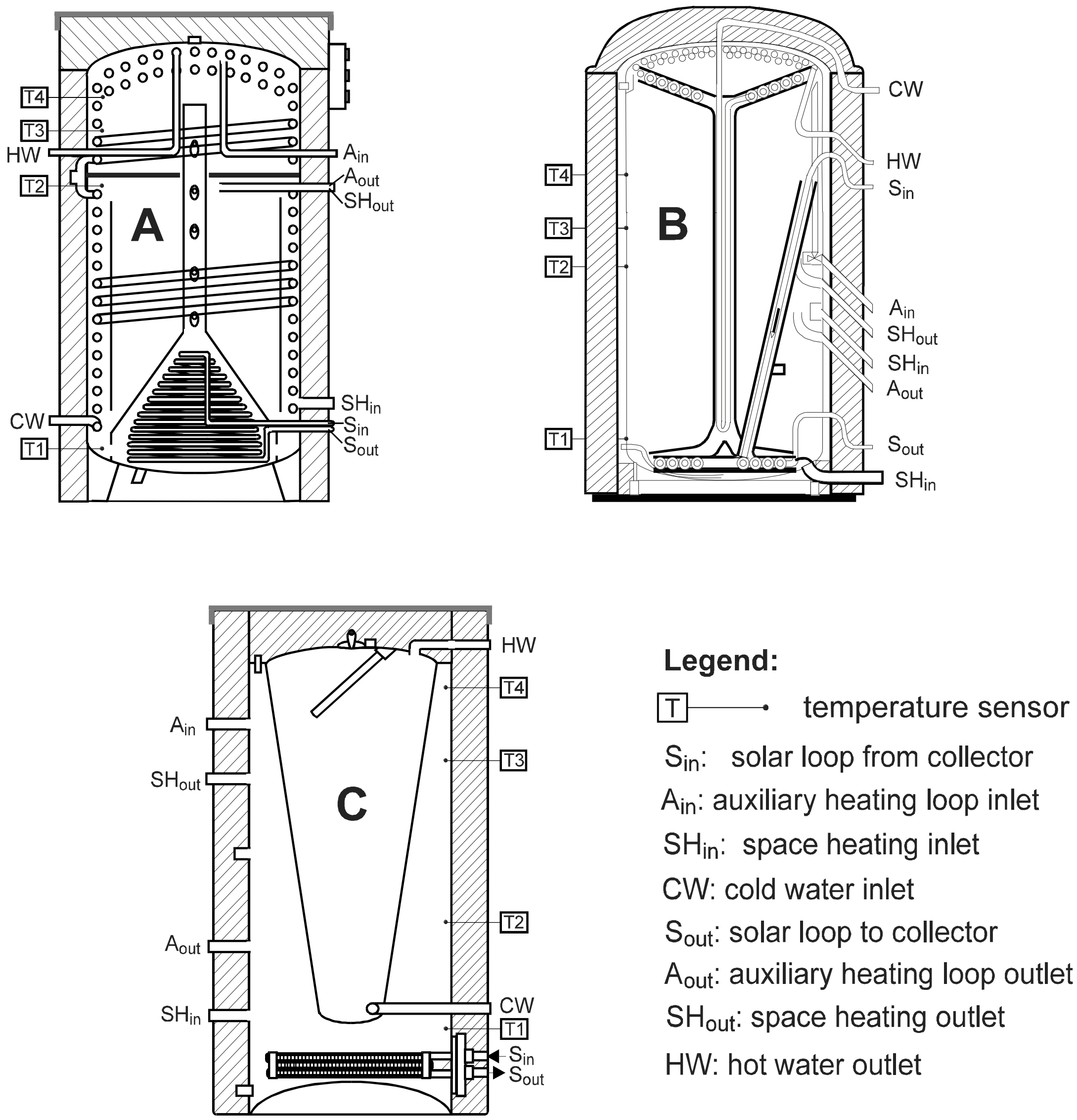

Figure 1: Schematic setup of the three combistores

4 Graphical presentation of the draw-off profiles

The figures 4.1 - 4.5 show the cold water inlet temperature (Tin), the hot water outlet temperature (Tout), the store temperatures at different heights of the store (relative height indicated in %) and the volume flow rate during the complete draw-off phase.

In order to investigate the influence of the draw-off profile on the determined 'utilised hot water volume' for store A, an additional test sequence was performed with a draw-off profile starting with 900 l/h, followed by 300 l/h and a final discharge with 600 l/h (the draw-off time for each flow rate was the same as for the 300/900/600 draw-off profiles).

In order to investigate the reproducibility of the test results, the experiment was repeated for store B. The two test sequences determined for store B are indicated as B1 and B2.

4.1 Store A

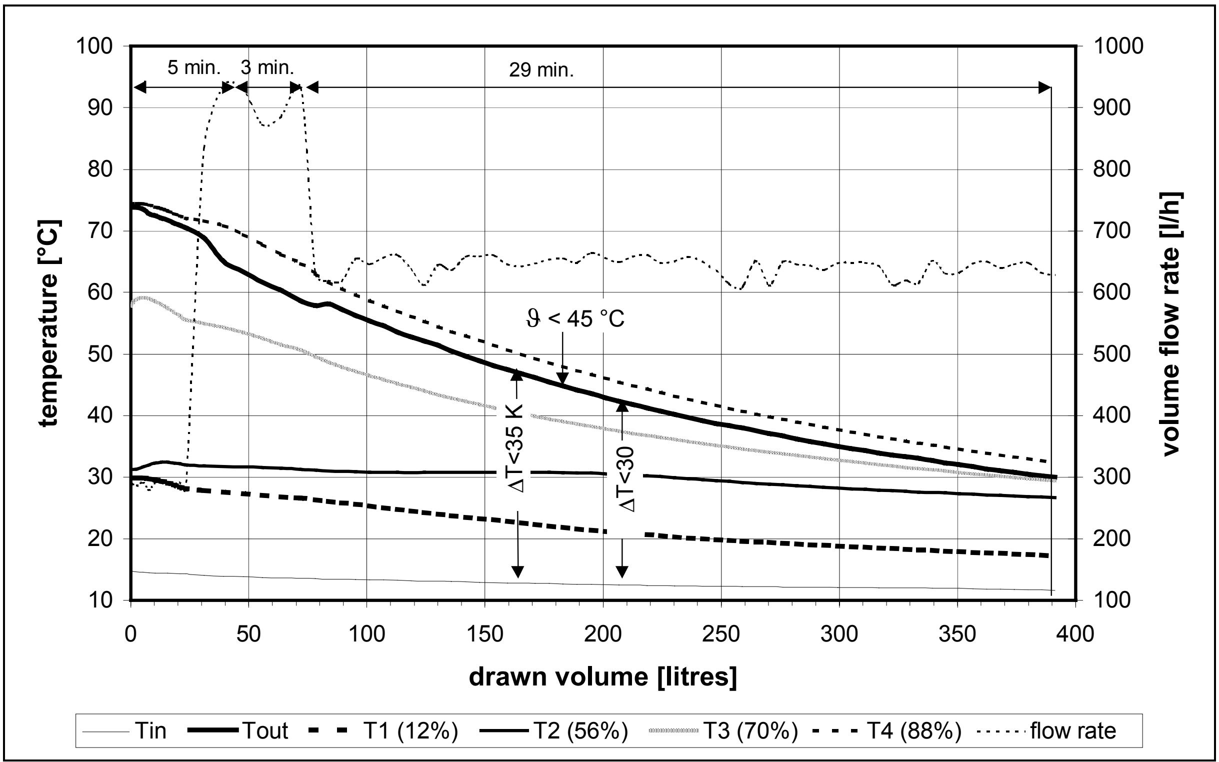

Figure 4.1:Temperatures and volume flow rate of store A (draw-off profile 300/900/600 l/h)

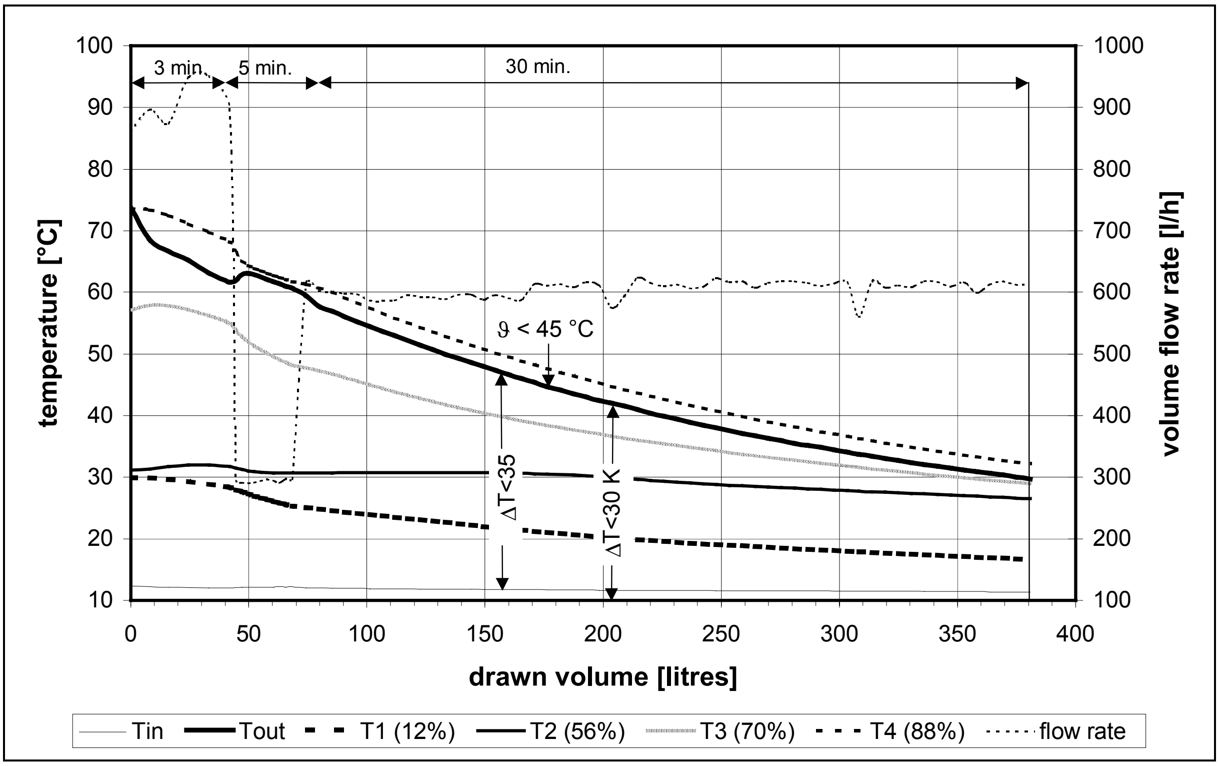

Figure 4.2:Temperatures and volume flow rate of store A (draw-off profile 900/300/600 l/h)

4.2 Store B

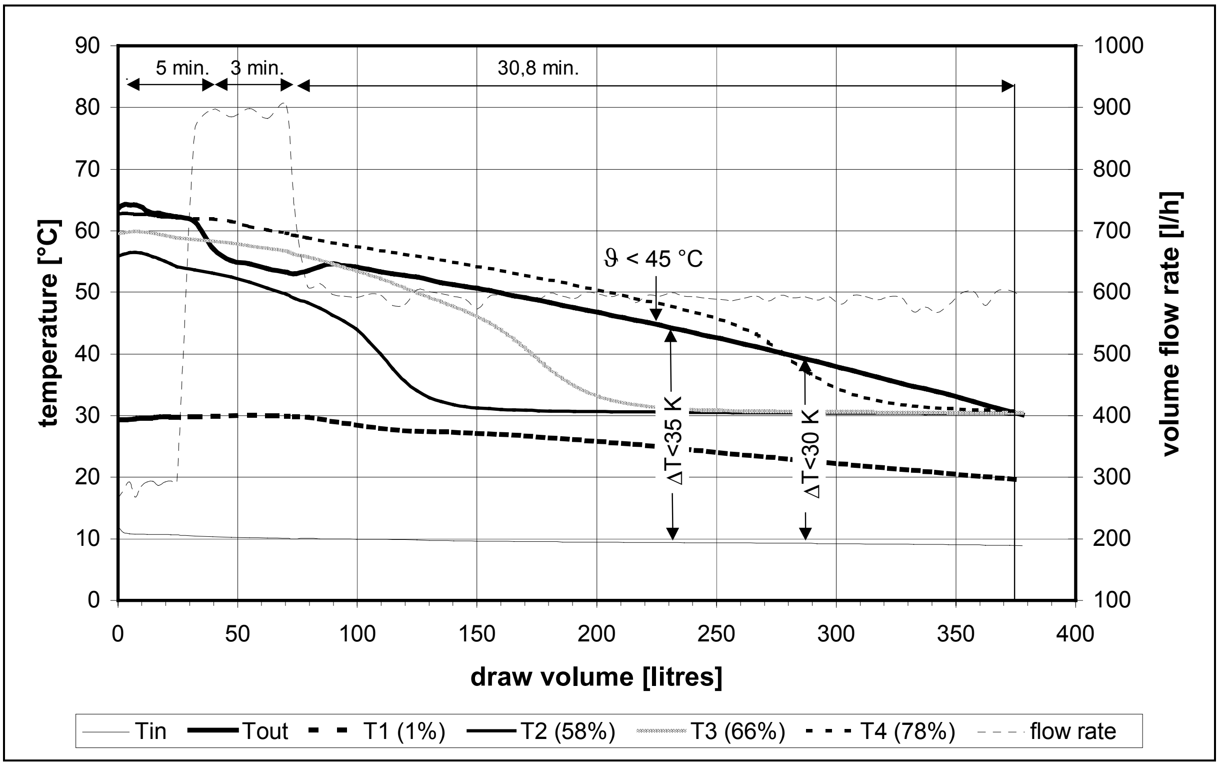

Figure 4.3:Temp. and vol. flow rate of store B (Test B1) (draw-off profile 300/900/600 l/h)

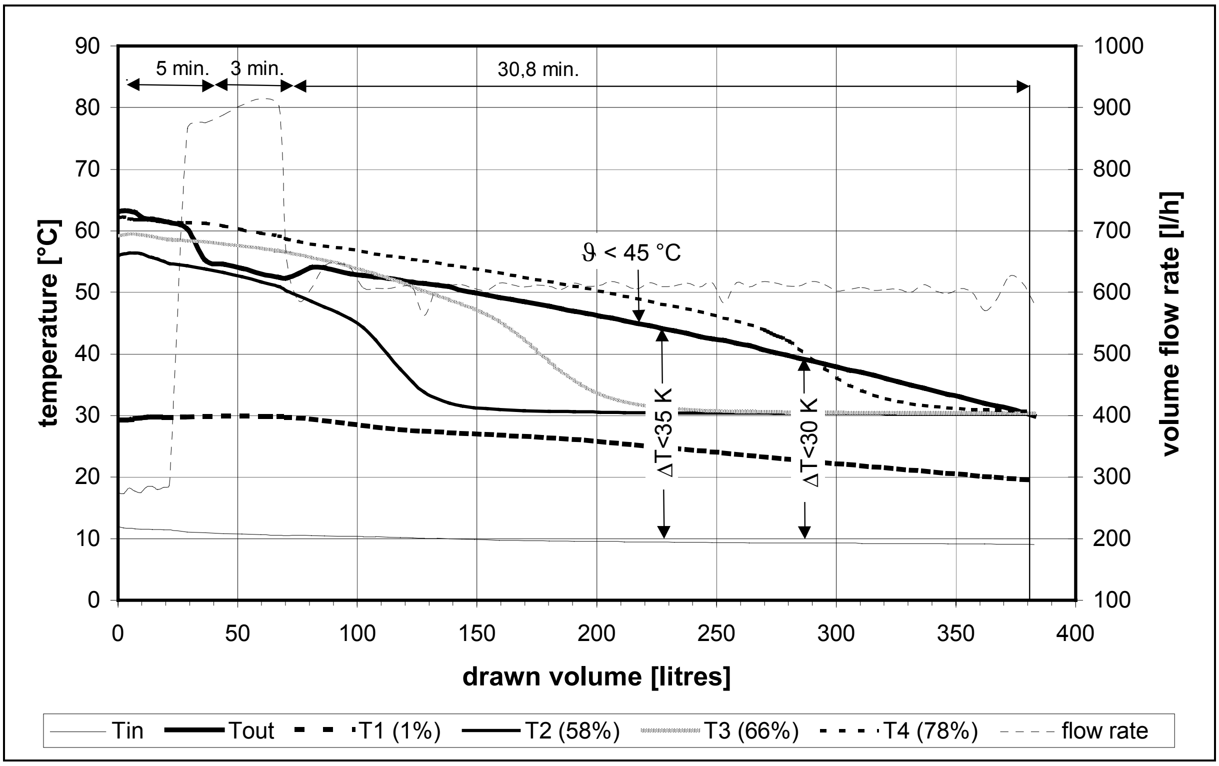

Figure 4.4:Temp. and vol. flow rate of store B (Test B2) (draw-off profile 300/900/600 l/h)

4.3 Store C

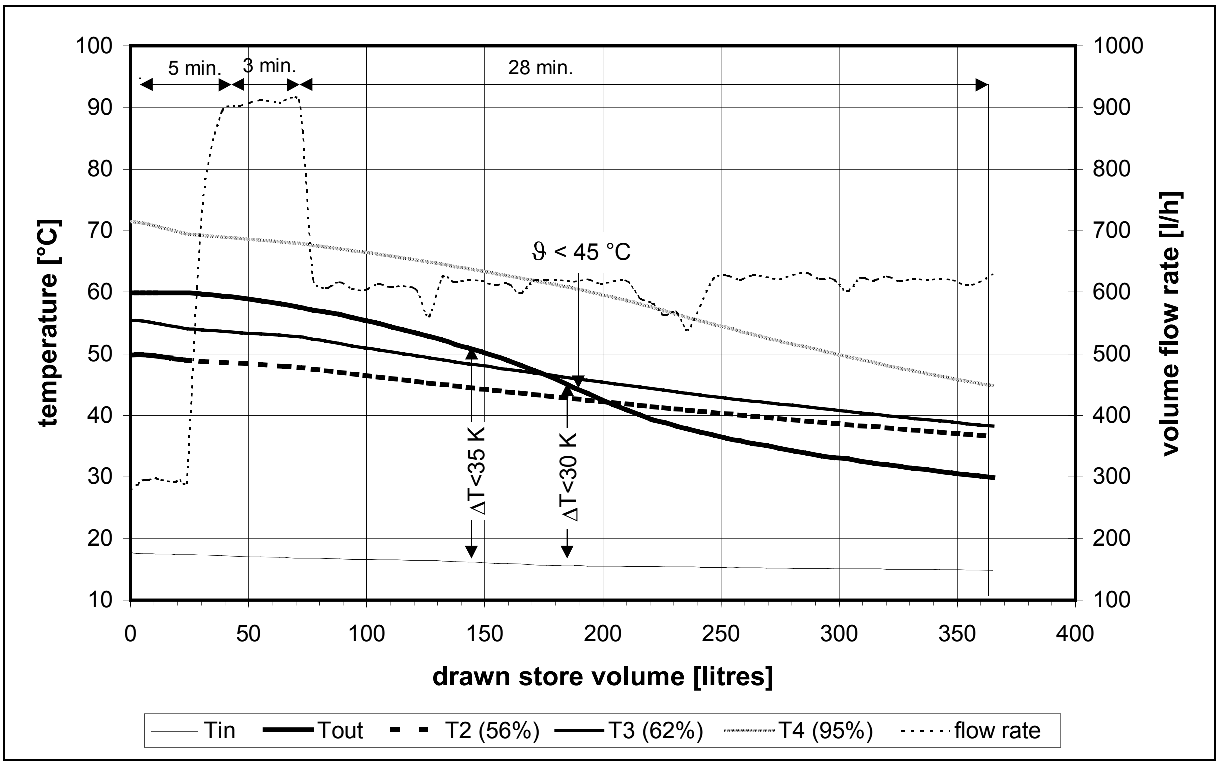

Figure 4.5:Temp. and volume flow rate of store C (draw-off profile 300/900/600 l/h)

5 Results

The values calculated for the heat discharged from the store on the basis of the three termination criteria are given in tables 2 and 3. Furthermore the cold water inlet temp. ϑ_{CW} and the hot water outlet temperature ϑ_{HW} at the time where the termination criteria was fulfilled are shown.

Table 2: Temperatures and amount of heat tapped from the store using a draw-off profile of 300/900/600 l/h

draw off profile 300/900/600 l/h										
criteria	**ΔT < 30 K**			ΔT < 35 K			ϑ_{HW} < 45 °C			
store	ϑ_{CW} [°C]	ϑ_{HW} [°C]	$Q_{HW,meas}$ [MJ]	ϑ_{CW} [°C]	ϑ_{HW} [°C]	$Q_{HW,meas,35}$ [MJ]	ϑ_{CW} [°C]	ϑ_{HW} [°C]	ΔT [K]	$Q_{HW,meas,45}$ [MJ]
A	12,5	42,3	-36,187	12,8	47,4	-29,950	12,7	44,8	32,1	-33,177
B1	9,2	39,2	-48,468	9,4	44,2	-41,030	9,4	44,7	35,3	-40,291
B2	9,3	39,3	-47,580	9,4	44,1	-39,240	9,5	45,0	35,5	-37.722
C	15,6	45,5	-28,899	16,2	51,0	-23,640	15,5	44,5	29,0	-29,565

Table 3: Temperatures and amount of heat tapped from store A using a draw-off profile of 900/300/600 l/h

draw off profile 900/300/600 l/h										
criteria	**ΔT < 30 K**			ΔT < 35 K			ϑ_{HW} < 45 °C			
store	ϑ_{CW} [°C]	ϑ_{HW} [°C]	$Q_{HW,meas}$ [MJ]	ϑ_{CW} [°C]	ϑ_{HW} [°C]	$Q_{HW,meas,35}$ [MJ]	ϑ_{CW} [°C]	ϑ_{HW} [°C]	ΔT [K]	$Q_{HW,meas,45}$ [MJ]
A	11,6	41,6	-36,590	11,7	46,6	-30,087	11,7	44,7	33,0	-32,370

As already mentioned, the utilised hot water volume V_{uhw} is calculated as the amount of water which can be heated up from 10 °C to 45 °C with the heat discharged from the store. Since three termination criteria were investigated for the calculation of that heat ($Q_{HW,meas}$, $Q_{HW,meas,35}$ and $Q_{HW,meas,45}$) three different values can be calculated for the utilised hot water volume (V_{uhw}, $V_{uhw,35}$, $V_{uhw,45}$). These values as well as the heat transferred to the store during charging of the auxiliary part Q_{aux} are presented in tables 4 and 5.

With regard to heat transferred to and discharged from the store, it has to be noted that the heat transferred to the store Q_{aux} is based on a temperature of 30 °C (temperature of the pre-conditioned store at the beginning of charging the auxiliary part). The heat discharged from the store is calculated, based on the temperature difference between cold water inlet and hot water outlet temperature and the volume flow rate. As a consequence of this, theoretically the heat discharged from the store can be larger than the one transferred to the store during charging of the auxiliary part.

Table 4: Heat transferred to the store during charging of the auxiliary part ($Q_{aux,meas}$) and utilised hot water volumes V_{uhw} determined for the different termination criteria using a draw-off profile of 300/900/600 l/h

draw off profile 300/900/600 l/h							
criteria		**ΔT < 30 K**		ΔT < 35 K		ϑ_{HW} < 45 °C	
store	Q_{aux}. [MJ]	$Q_{HW,meas}$ [MJ]	V_{HW} [l]	$Q_{HW,meas,35}$ [MJ]	$V_{HW,35}$ [l]	$Q_{HW,meas,45}$ [MJ]	$V_{HW,35}$ [l]
A	38,774	-36,187	249,2	-29,950	206,3	-33,177	228,5
B1	51,815	-48,468	333,8	-41,030	282,6	-40,291	277.5
B2	51,482	-47,580	327,7	-39,240	270,3	-37,722	259,8
C	48,106	-28,899	199,0	-23,640	162,8	-29,565	203,6

Table 5: Heat transferred to store A during charging of the auxiliary part ($Q_{aux,meas}$) and utilised hot water volumes V_{uhw} determined for the different termination criteria using a draw-off profile of 900/300/600 l/h

draw off profile 900/300/600 l/h							
criteria		**ΔT < 30 K**		ΔT < 35 K		ϑ_{HW} < 45 °C	
store	Q_{aux}. [MJ]	$Q_{HW,meas}$ [MJ]	V_{HW} [l]	$Q_{HW,meas,35}$ [MJ]	$V_{HW,35}$ [l]	$Q_{HW,meas,45}$ [MJ]	$V_{HW,35}$ [l]
A	37,870	-36,590	252,0	-30,087	207,2	-32,370	223,0

Figure 5.1 shows a summary of the results for the utilised hot water volumes determined for different termination criteria and draw off profiles. The values are given in percent; 100 % correspond to 200 litres.

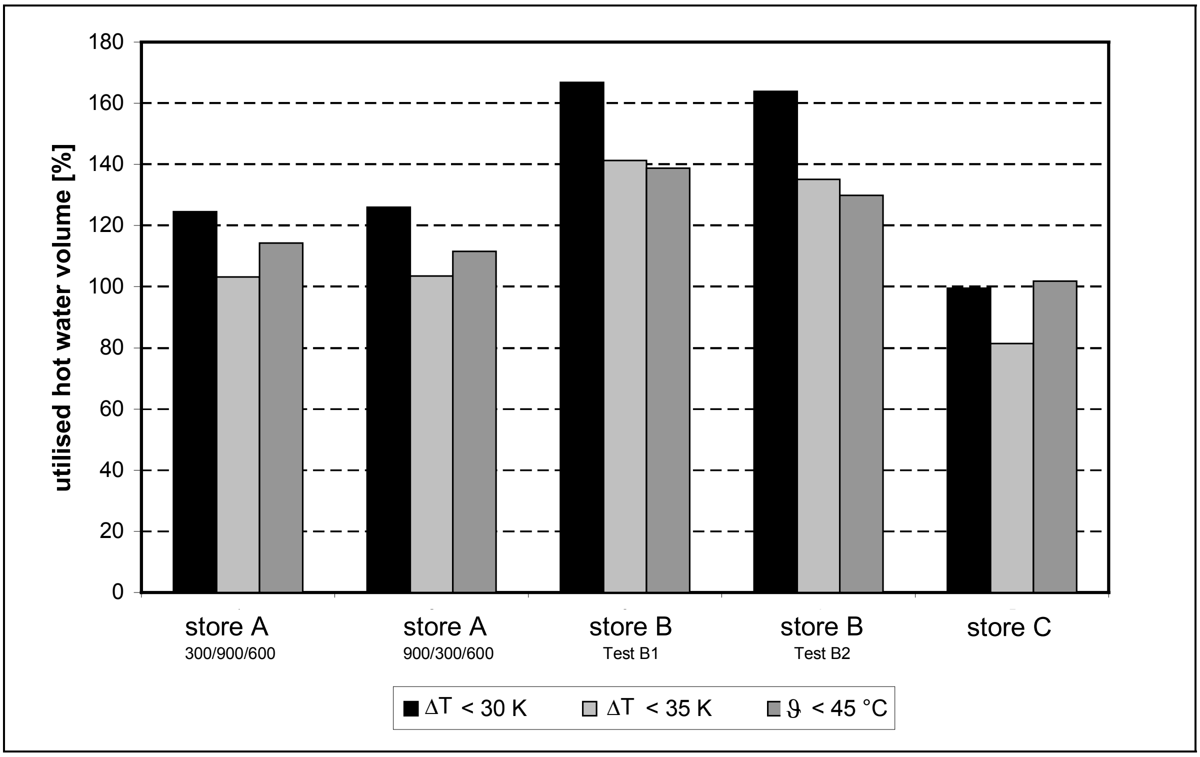

Figure 5.1: Utilised hot water volumes in percent (100 % correspond to 200 litres) determined for different termination criteria and draw off-profiles.

6 Summary

The two tests of store A carried out with different draw of profiles (300/900/600 l/h and 900/300/600 l/h) show that the influence of the draw-off profile is quite small. The repeated test carried out with store B (Test 1 and Test 2) delivered nearly the same results for the utilised hot water volume. For the proposed termination criteria of ΔT < 30 K the deviation is approximately 2 % which is within the measuring accuracy.

Both effects, the negligible influence of the draw-off profile as well as the high reproducibility of the test results, were also confirmed with tests carried out with several other stores. Due to objections of some manufacturers these results may not be published.

The diagram and tables show that the proposed termination criteria of ΔT < 30 K leads to the largest values for the utilised hot water volume V_{uhw}. This result could be expected because it is the 'weakest' criteria. However it was chosen, since the termination criteria of ΔT < 35 K may lead to problems if the hot water preparation concept of the store is designed for a hot water outlet temperature of 45 °C and if a cold water inlet temperature of 15 °C is used.

The termination criteria of ϑ_{HW} < 45 °C was found not to be appropriate, because the results determined in this case will strongly depend on the cold water inlet temperature.

An additional advantage of the termination criteria ΔT < 30 K is that the utilised hot water volume determined for this criteria delivers the most stable and reproducible values. This can be seen from the two tests carried out with store A and B.

It can be concluded that the proposed test procedure is suitable for the characterisation of the hot water performance of solar combistores. The investigations and considerations showed that the termination criteria ΔT < 30 K is the appropriate one for the calculation of the utilised hot water volume.