Development of a Buried Hot Water Storage – Measurement and Simulation

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1. Introduction

In order to achieve high solar fractions in heating systems of single or multi family houses, large collector areas and storage volumes are needed. In most cases this storages are placed in the basement of the building, where low room height and small entrances limit the possible storage volumes. Thus large storage volumes are only possible by on-site fabrications or by assembling of small tanks to a storage cascade. Both ways are complex and expansive solutions and occupy much space in the basement (Wilhelms, 2008). In addition, the thermal losses increase, as surface to volume ratio increases significantly with tubed tank cascades.

A new approach is to place the storage tank outside of the building in the underground. Within a research project[1] the ISFH develops a new storage concept for this application. The concept is based on a prefabricated container made of concrete, which is best suited for a long-term operation in the ground, and new developed insulation foam, which has a long-term stability at a temperature of 95°C even under a certain mechanical load, which occurs in such a tank. The tank is designed to operate at about ambient pressure, whereby different expansion concepts are investigated. The work includes the development and experimental investigation of two prototypes and a simulation study, in order to determine the operation capability and the optimum integration in solar assisted heating systems. For this purpose a simulation model was developed and implemented in TRNSYS for calculating the interaction between the soil and the buried hot water storage.

The paper discusses the main steps of the concept investigations and the results of a simulation study.

2. Storage concept and measurement results

To offer a cost efficient product with a high quality the construction time by the assembly should be reduced to a minimum. Only the excavation, the connection of buried pipes and the refilling of the hole around the tank should be carried out on site. The storage has therefore to be prefabricated and delivered by the manufacturer of the concrete cistern.

2.1 Construction of the first prototype

The external envelope of the storage is a cylindrical concrete cistern, manufactured by the company Mall, which protects the storage from ground water, roots, rodents and damages during installation. Inside the cistern a new foam insulation material based on XPS (extruded polystyrene foam) is placed, developed by BASF SE. Compared to standard XPS the new material reaches a high long-term stability at a temperature of 95°C, with a 20% higher pressure resistance (according to DIN EN 826). Because the new material is based on the XPS production process the insulation material can only be manufactured in the shape of panels, which have to be adapted by bending into the cylindrical cistern. In the first prototype three T-shaped profiles were used, which fixed the panels at the concrete mantle in its cylindrical form. The insulation of the bottom and the cap was made of custom-built panels. Therefore the bottom insulation panels were cut and matched for fitting into a circular form and the cap insulation panels were cut into “pie slices”. The storage

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water is kept by an inliner combination of two foils. The inner foil is a flexibel watertight EPDM foil container (Ethylene-Propylene-Dien-Monomer), which adapts its shape due to the temperature induced volume expansion of the water. It is connected to a floating flange, which can float up and down during charging and discharging cycles. The outer foil is a compund foil (PET/ALU/HDPE), which reduces the diffusion of water vapor to a minimum and thereby prevents the insulation from moisture penetration.

The first prototype was installed and measured in 2010. The storage volume was 5.45 m³ and the insulation thickness was 18 cm at the mantle and the bottom and 24 cm on top (k = 0.035 W/mK). Fig. 2.1 shows the concept of the first prototype. Differing from Fig. 2.1, the first prototype did not have any internal heat exchangers. It was charged and discharged directly.

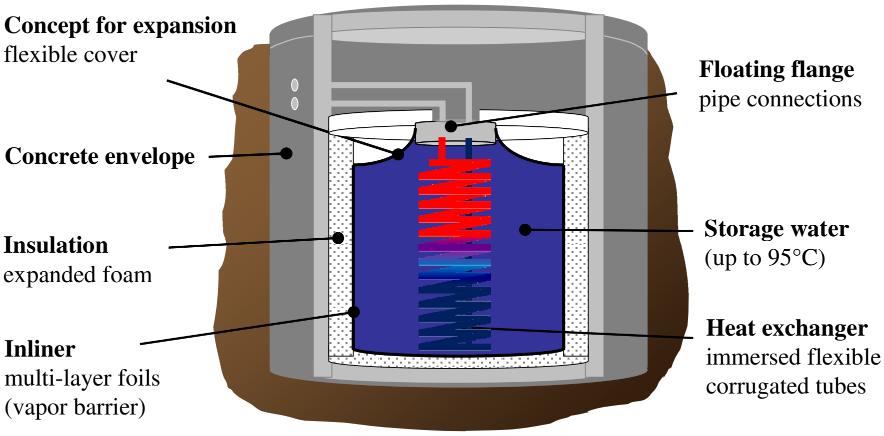

Fig. 2.1: Concept of the 1. prototype, here shown with internal heat exchanger, developed and measured at ISFH in 2010

2.2 Measurement results of the first prototype

The heat loss (UA-value) of storages is calculated from the reduction of the enthalpie during the measurement, the measurement period and the mean temperature difference between the storage and the ambient. In the first measured cooling curve the storage has shown a heat loss coefficient of 5.0 W/K ± 1.6%. The mean storage temperature thus decreases by 1.05 K per day for a storage water temperature decrease from 85°C to 65°C. Fig. 2.2 shows the measured cooling curve of the first prototype over a time period of 500 h. Due to only slight stratification effects, just the top layer and the five bottom layer temperatures inside the storage water are displayed (15 equally spaced temperature sensors are installed).

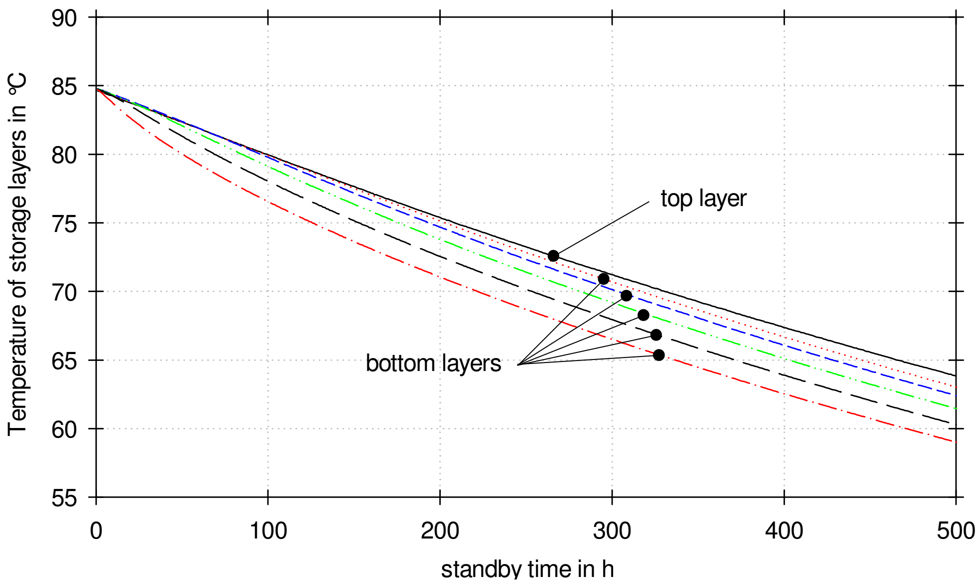

Fig. 2.2: Cooling curve of the first prototype, temperatures of the top layer and the 5 bottom layers (total 15 layers)

Further cooling curves were measured with changing operation parameters for the storage and its environment. After five operating cycles with heating up the storage water to 85°C and cooling down to 15°C the UA-value increased to 5.2 W/K because of disarranged insulation panels on the cap insulation. The construction with the top insulation panels lying on the floating flange thus has proved to be not suitable for long-term usage. A further measurement with repaired top insulation and with water saturated surrounding soil resulted in an increase of the UA-value of 0.3 W/K to 5.3 W/K. Another test was carried out after a modification of the expansion concept. An air volume above the water level inside of the EPDM-foil was established, which is communicating with the air in the cavity above the insulation. In this case the UA-value increased by about 0.1 W/K up to 5.1 W/K. Thus, no significant higher heat losses caused by the air and water vapour exchange are to be expected. Via simulation it could be shown, that condensation of the vapour in the upper air volume is no major problem even if condensation occurs inside of the cistern.

The heat losses of the first prototype show with UA-values of around 5 W/K good results. The storage is well insulated and remains rather unimpressed on changes of ambient parameters, especially the variant with communicating air cushion to compensate the volume expansion of the water has nearly the same heat losses like the closed storage with floating flange. Consequently the storage concept with communicating air volume appears as the better solution, especially because its construction is much easier.

2.2 Deconstruction of the first prototype

After an operation period of four month, mainly at high temperature (between 60 and 95°C), the storage has been disassembled. During the deconstruction the storage was investigated for water accumulations and changes in materials. At the outside of the two foils, between the compound foil and the insulation, no moisture could be found. Also between the both foils no significant amount of water has been found. Only several water drops have been determined, so it can be assumed, that the aluminium compound foil has successfully reduced the water vapor diffusion, only the air between the foils is expected to be saturated with water vapor. So the construction of a foil based container storing the water volume with temperatures up to 95°C is possible.

Fig. 2.3: Deconstruction of the first prototype, on the left side storage with compound foil, floating flange and replaced cap insulation – on the right side removed insulation panels of the storage wall insulation

After the deconstruction the storage components were analyzed. Between and inside of the insulation panels no moisture accumulation has been observed. The inner insulation panel of the bottom insulation with the highest temperature exposure showed a small compression in comparison to the other panels (about 1% of the insulation panel thickness related to the mean value of the other panels). The other insulation panels did not show a measurable compression. The EPDM-foil appeared unchanged and has been used again for the second prototype. The aluminium compound foil showed partially a delamination of the compound. In addition to that, the aluminum layer in the centre the compound displayed little holes at the kinks, which could not be avoided during the assembly process. It may be assumed, that the water vapor diffusion thereby is increasing. The outer foils of the compound however looked unchanged. Regardless of that, the insulation panels and the EPDM-foil can be considered as suitable for the storage concept. Concerning the aluminium compound foil an alternative material with higher stability is necessary.

2.3 Construction of the second prototype

In the concept of the first prototype a floating flange was used to compensate the volume expansion of the water by increasing temperatures. Thereby the flange moved up to 8 cm up and down during charging and discharging. The top insulation lies on the rim of the flange whereby the inner circle of the insulation was also moving. Thereby the insulation, made of “pie slices”, has been disarranged and the heat losses of the storage increased. In addition to that the manufacturing of “pie slices” requires a lot of time and results in large cutting losses of insulation material. Because of these facts the concept of the second prototyp has been changed.

The second prototype was installed in spring 2011. Changes were made on the cap construction of the insulation, the fixing of mantle insulation and the charging and discharging device, where an internal heat exchanger has been implemented. The insulation of the cap is made with panels, which lie on the mantle insulation and on the flange, which is now in a fixed position. The cap and bottom insulation with panels can be manufactured with a master plate in one step. The T-shaped profiles, which fixed the mantle insulation in the cylindrical cistern have been found to be not necessary and could therefore be removed. The mantle insulation panels hold each other in cylindrical form when under tension. In addition to that the second prototype is equipped with internal heat exchangers. This is necessary, as the tank is operated at low pressure and it is located under the ground level. To load the storage directly would lead to cavitation effects. The heat exchanger is separated in three zones, each with the same length. The fluid can pass one, two or all zones with changeable direction, which allows a partly stratified charging or discharging. Furthermore the concept to compensate the volume expansion of the water has been changed from the floating flange to an “open operation”. The new concept provides an air volume inside the inliner and above the water level, which communicates with the atmospheric air. With increasing storage temperatures the air can leave the inliner and the flange and the top insulation is fixed. Therefore the water volume had to be reduced to 5 m³.

2.4 Measurement results of the second prototype

During the first heat loss measurement the storage reached a heat loss of 4.93 W/K ±1.6%. The temperature decrease of the storage water was about 1.1 K/d. Fig. 2.4 shows the first measured cooling curve of the second prototype.

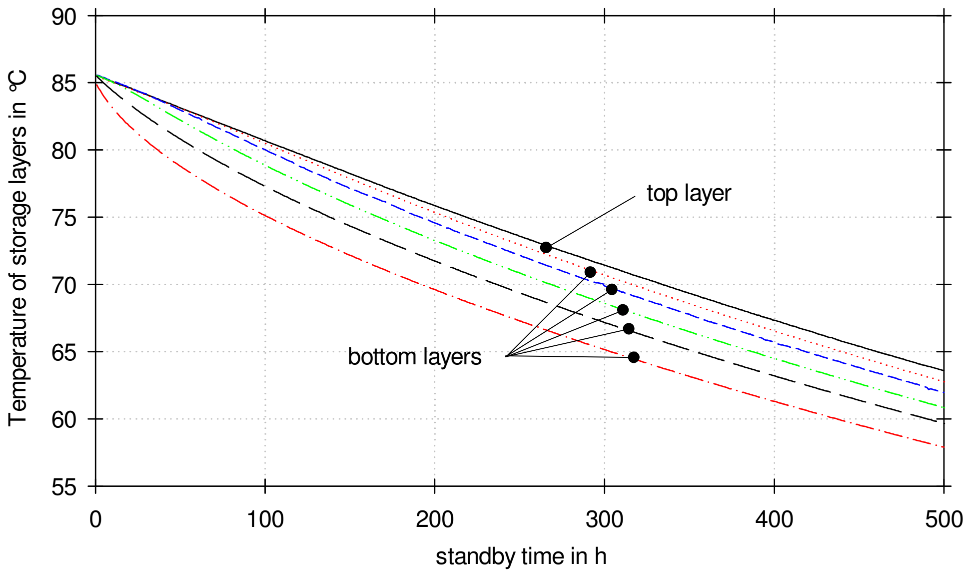

Fig. 2.4: Cooling curve of the second prototype, temperatures of the top layer and the 5 bottom layers (total 15 layers)

In comparison to the first prototype the temperatures of the bottom layers decrease faster, because the internal heat exchanger increases the vertical heat conduction inside the storage water. In comparison to a steel tank, where the mantle contributes a significant portion, the vertical conductivity is mainly caused by the conductivity of the water and the metallic built-in components. Typically, the vertical conductivity is three times higher in a steel tank. In addition to that a small dead water volume exists under the heat exchanger, which can not be charged. So the temperature decrease of the storage is marginally higher if compared to the first prototype. Apart from that the heat loss is somewhat lower than by the first prototype because of the reduced water volume. Consequently, the second prototype has nearly the same properties like the first one, but the storage concept was optimized which could clearly reduce the time for the assembly and the reliability of operation. Fig. 2.5 shows a comparison of the measured parameters of the prototypes.

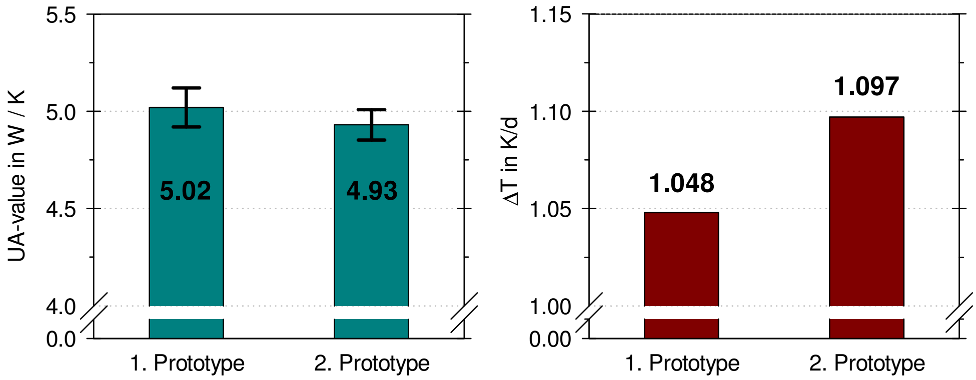

Fig. 2.5: Comparison of the heat losses and average temperature decreases of the storage water between 85°C and 65°C for the first and the second prototype

The measured loss coefficients of about 5 W/K are, if compared to numerical FEM simulations, only about 5% higher than the theoretical values. This supports the assumption, that the construction is nearly free of thermal bridges and other undesired loss mechanisms. However, an important criterion in ground-based storages is the way to connect the pipes, which enter the tank at its top. It has been found out, that water convection inside the connecting pipes enlarges the heat losses by about 0.2 W/K per pipe, if no heat traps are installed.

2.5 Following measurements of the second prototype

Corresponding the measurements of the first prototype, heat loss measurements after several load cycles will be carried out. Performance measurements for the internal three zone heat exchanger are foreseen to determine the possibility of stratified charging. At the end of the experimental phase, a stepwise increasing moisture content and finally a completely damaged inliner will be realized. This seems to be necessary, because it may be stated, that unwanted water in the insulation has always a high risk in ground located storage tanks. In addition, a measurement without storage insulation and high storage temperature should allow the validation of the new soil simulation model (see chapter 3.2). Finally the storage components will be investigated again during and after the deconstruction.

3. Simulations

Beside the storage development, a heating system for a residential building including a soil buried hot water storage is simulated in TRNSYS, basing on the IEA SHC Task 32 system (Heimrath, 2007). For this purpose, a new TRNSYS type which models the surrounding soil of the storage has been developed. For the storage itself the TRNSYS type 340 (Drück, 2006) was used. Both types are linked by the nodes of the storage (type 340) and the contact temperatures of the concrete cistern (type surrounding soil).

3.1 Changes on TRNSYS-Type 340 (MULTIPORT Store Model)

Because of the different earth temperatures along the storage height, it was necessary to adapt the type 340 to a new version, which uses a corresponding ambient temperature for each temperature node of the storage. The new inputs are connected with the contact temperature outputs of the new type for the surrounding soil.

3.2 TRNSYS-Type Surrounding Soil

For the simulation of the surrounding soil a model with a transient two-dimensional temperature field has been developed. Starting from the undisturbed earth temperature, parameterized with the meteorological data of the used weather zone and with the properties of the soil, the influence of irradiation, air speed and sky temperature are considered. Thereby a presimulation of about 10 years is necessary to get the undisturbed earth temperature, which is known for the location under consideration. After that a regular simulation can be started any further changes in the soil are caused by the buried storage.

Tested in TRNSYS:

The developed type was compared to the TRNSYS type 501 (soil temperature profile), based on a formula of (Kasuda, 1965). The type 501 does not use any inputs and is parameterized with the mean values of the used weather zone. For the comparison the new type was parameterized with a small storage with extremely well insulation, so that no heat flow is appearing between storage and soil and the surrounding soil can be assumed to be undisturbed. In deep soil layers the temperatures of the new type are almost identical with the temperatures of type 501. In the upper soil layers the new type deviates from the sinus curve of the type 501, because of the influence of the used meteorological inputs in combination with the surface properties, what could have been expected..

Furthermore the storage heat loss flow was investigated, starting from an undisturbed soil, with a constant storage temperature and under the influence of the weather conditions. Therefore the new type was parameterized with a storage of 5.5 m³ water volume, an insulation thickness of 0.2 m (k = 0.035 W/mK) and a constant water temperature of 80°C. Like in the prototypes, the storage has an air space for the pipe connection above the insulation, inside of the cistern, in all simulations set to a height of 0.5 m. The temperature distribution resulting from the heat loss flow of the storage is shown in fig. 3.1, starting from the undisturbed soil temperature after the time of 1 day, 1 week and 1 month.

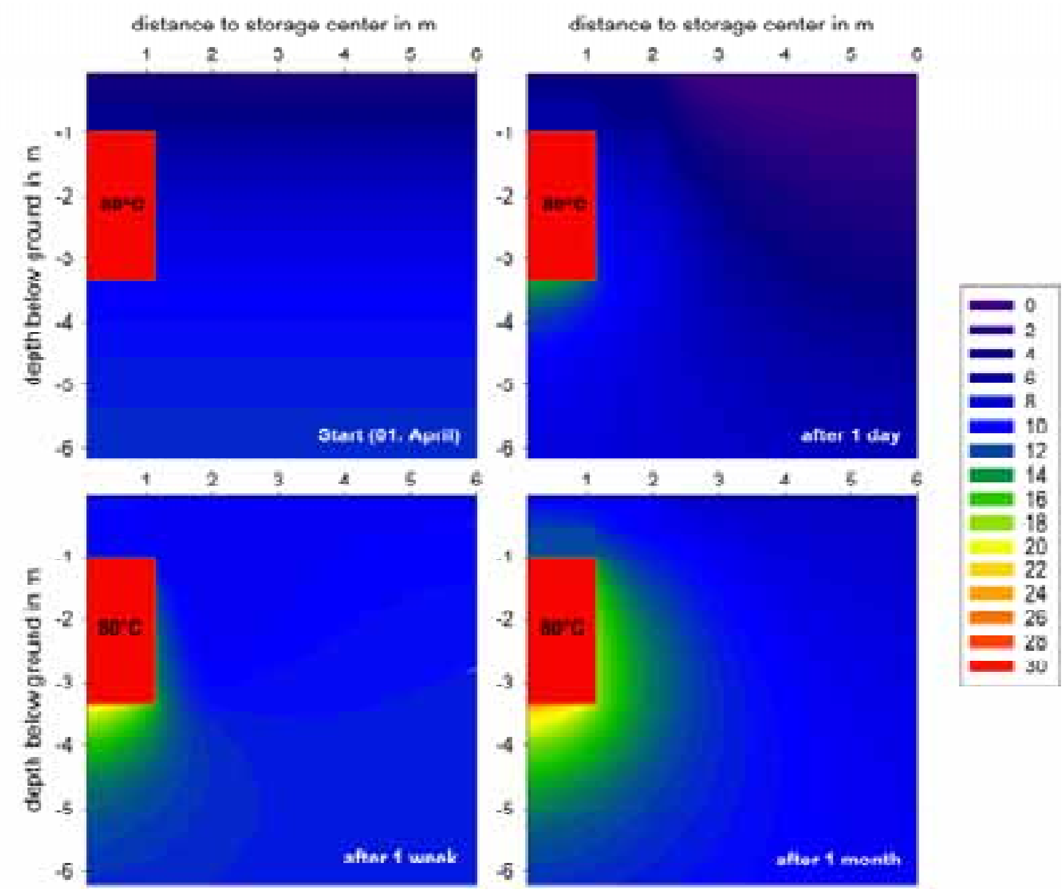

Fig. 3.1: Temperature of storage surrounding soil during a period of one month with a constant storage temperature of 80°C, (0.2 m insulation thickness, k = 0.035 W/mK) with the influence of weather data, at start time (01. April), 1 day after start, 1 week after start and 1 month after start

Above the storage the heat flows to the soil surface where it is transferred by convection and radiation to the ambient air and the sky. Below the storage, the heat flow is limited by the thermal conductivity of the surrounding soil. This leads to a temperature increase in the part around the tank. Consequently the heat losses of the storage decrease after a time period with high water temperature, especially at the bottom of the storage, caused by the warmer surrounding soil.

Because of the rather low heat losses of the prototypes and the rather high distance of the nearest set of sensors (0.5 m to the storage), an experimental validation of the model was up to now not possible. However, plausibility checks have successfully been carried out. As a further test, the operating of the storage without insulation at constant high water temperature is foreseen, where a remarkable temperature increase in the ground should be measurable.

3.3 System simulations; basic conditions

For the simulations in TRNSYS 16 the IEA SHC task 32 system (Heimrath, 2007) was modified and adapted to the buried hot water tank boundary conditions, with the requirement, that the buried storage is only loaded by solar energy, which will be used for increasing the return flow temperature of the boiler. A small domestic hot water tank is located within the building. The load of the DHW storage (set temperature 63°C) has priority. For all simulation runs, the simulated period was 2 years, of which the second was used for evaluation. Seasonal effects beyond 2 years were not detected.

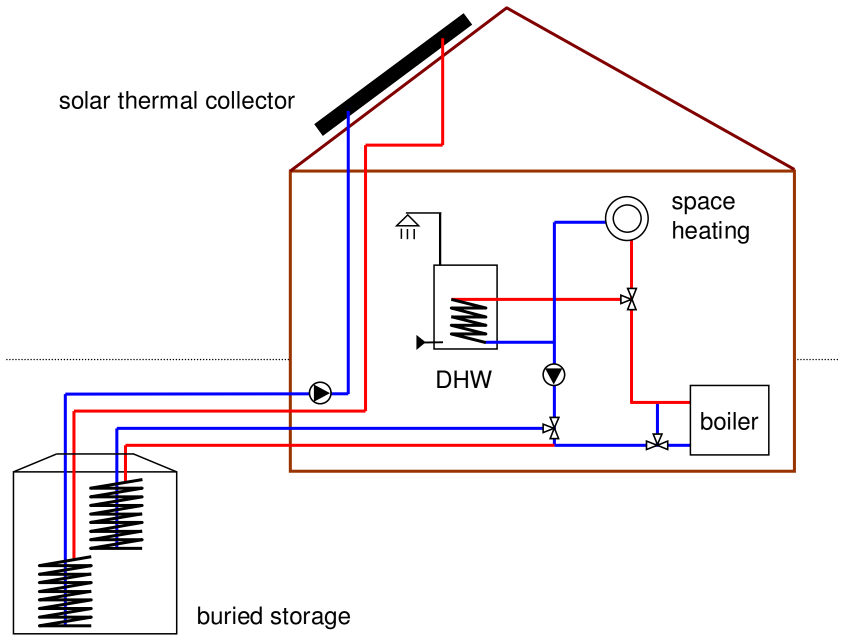

Fig. 3.2: System scheme of the simulated solar assisted heating system. Buried hot water tank is only loaded by solar energy and is used for increasing the return flow temperature of the boiler.

The buried hot water storage is parameterized according to the second prototype with internal heat exchangers. The insulation thickness is 0.2 m (k = 0.035 W/mK) and the storage height is for volumes lower than 20 m³ limited to 3 m, lower than 5 m³ to 2.5 m and lower than 2 m³ to 2 m because of the project approach to develop a prefabricated storage, which has to be transportable and easy to install. As reference climate the Meteonorm weather data of Zurich (Switzerland) were used. The collector orientation is south with a slope of 45°. Unless otherwise noted a building with a heat load of 60 kWh/m²a is used. The boiler model was taken from (Haller, 2009). For the evaluation of the solar fraction the fractional solar saving indicator f_{si} is used (Heimrath, 2007), (eq. 3-1).

$$f_{si} = 1 - \frac{\frac{Q_{boiler}}{\eta_{boiler}} + \frac{W_{el}}{\eta_{el}} + Q_{penalty} - Q_{penalty,ref}}{\frac{Q_{boiler,ref}}{\eta_{boiler,ref}} + \frac{W_{el,ref}}{\eta_{el,ref}}} \qquad \text{(eq. 3-1)}$$

3.4 Simulation results

In all simulations the simulation system was parameterized with the basic conditions, unless it is explicitly pointed out. In comparison to storage volumes parameterized with a height to diameter ratio of 1 the storages parameterized with the basic conditions have nearly the same solar fractions in the range from 1 m³ to 20 m³ storage volume.

Variation of storage volume and collector area:

The simulation results show a high dependency of the solar fraction on the collector area. In contrast the storage volume sensitivity is lower than expected. Starting from the volume of 1 m³ the solar fraction rapid increase and remain or decrease for larger storage volumes (fig. 3.3). In the simulation system the prototype storage with 5 m³ achieves a solar fraction of 35% with 30 m² collector area and 44% with 50 m². To use a larger storage does not lead to a significant increase of the solar fraction. On the contrary, it is thinkable to reduce the storage volume for 30 m² to 2 m³ (- 2% solar fraction) and for 50 m² to 3 m³ (-1%). While the optimum storage to collector ratio is about 200 l/m², a ratio of 70 l/m² only results in a minor penalty. This will be discussed more in detail in the following.

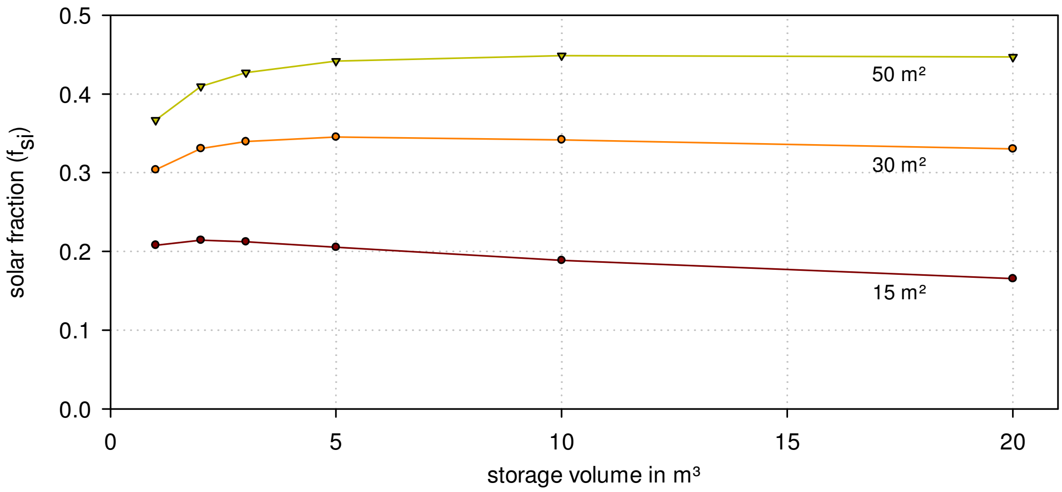

Fig. 3.3: Solar fraction (f_{si}) as a function of the storage volume for several collector areas, parameterized with the basic conditions

In addition to the collector area the heating load of the building is important. E.g., if instead of 60 kWh/m²a a building with a heating load of 30 kWh/m²a has to be supplied, the solar fraction is 7% points higher, while with 100 kWh/m²a building it will be 9% points lower, in all cases basing on a system with 5 m³ storage volume and 50 m² collector area.

The solar fraction values shown in Fig. 3.3 are lower than known from other simulation studies carried out with the Task 32 system. One main reason is, that here in all simulations the collector energy is directed to the buried storage, before used in the building. Both the charging and the discharging, as the tank is pressure-less and needs internal heat exchangers, cause temperature gradients and, as stratification is affected by internal heat exchangers, a more pronounced mixing occurs. Further simulations will show the effect, if the building is supplied with collector heat with priority, and only excess heat is stored in the buried tank. Higher solar fractions are expected. Another modifcation will be additional heat exchangers: the solar heat exchanger in the upper part and a discharge in the bottom part.

There are two main reasons for the relatively low increase of the f_{si} curve with higher storage volumes.

- As the the insulation thickness of the storage is kept constant (0.2 m, heat conductivity of 0.035 W/mK), heat losses increase for larger storage volumes. Although large storages lead to a higher solar yield, this benefit is partly compensated by the higher losses. For this reason, the solar fraction increases rapidly at small storage volumes and slowly at large ones.
- Secondly, the time shift in case of a large volume is high, i.e. the storage may deliver heat to the building for a longer period, however, the large storage stays longer cold if heated up again in spring. This will be shown in Fig. 3.4.

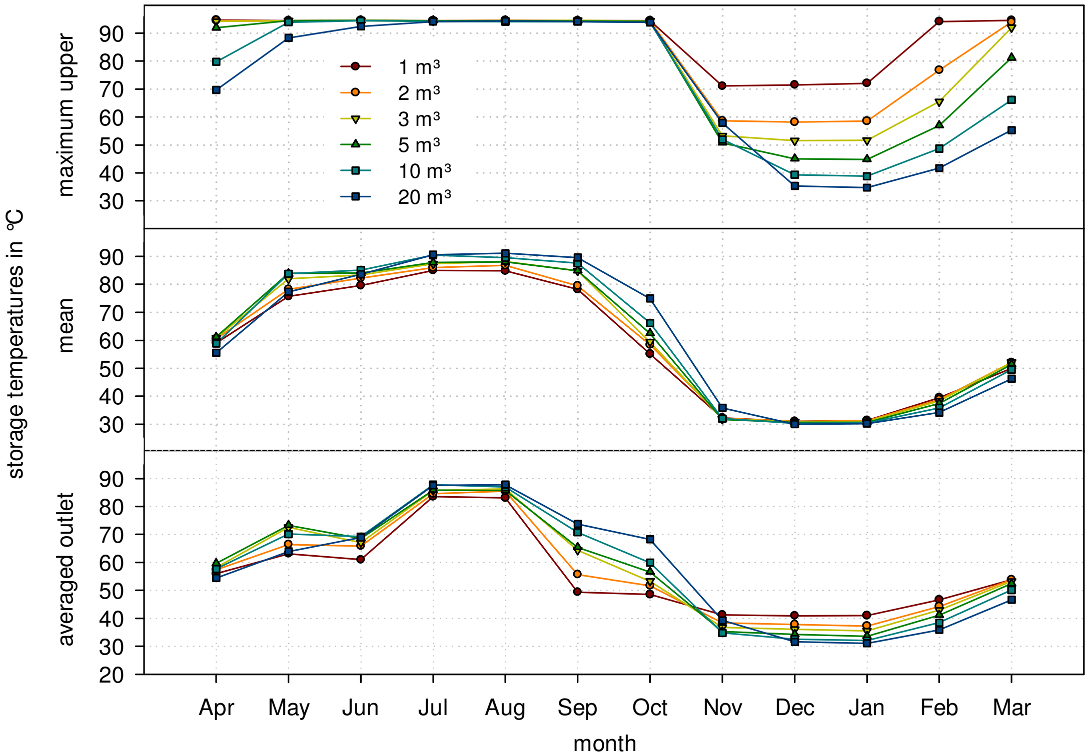

Fig. 3.4: Storage temperature distribution over one year for different storage volumes, collector area 50 m² - top graph: the maximum upper storage temperature, graph in center: mean storage temperature, bottom graph: averaged storage outlet temperature (return flow of the boiler)

Consequently, smaller storages with fast dynamic reach nearly the same solar fractions and the enlargement of the storage is to be recommended only to a certain level. This effect is more pronounced in a storage tank, which is charged and discharged via internal heat exchangers, than in a buffer tank with stratification supporting devices.

The following diagram shows the influence of the thermal conductivity of the insulation on the solar fraction.

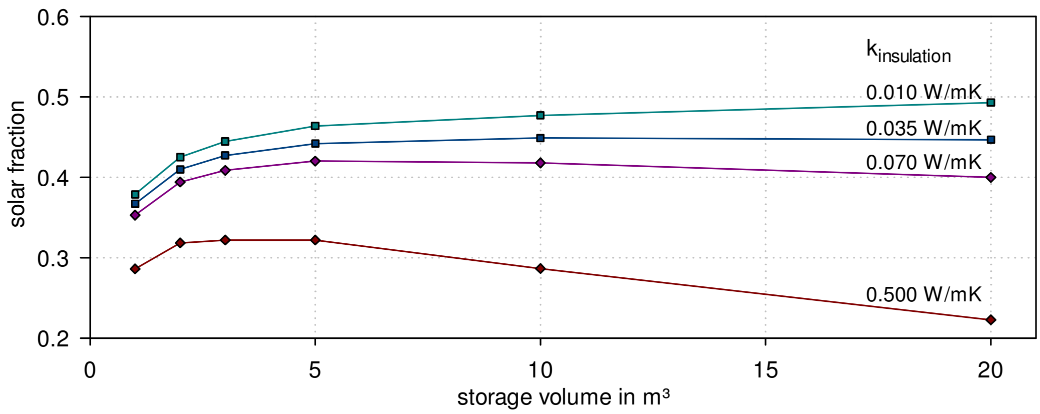

Fig. 3.5: Influence of the thermal conductivity of the insulation on the solar fraction for a collector area of 50 m² (insulation thickness 20 cm)

It is shown that the thermal conductivity of the insulation has a lower influence as expected, especially for small storage volumes. With a collector area of 50 m² and a storage volume of 5 m³, a variation of the thermal conductivity to 0.01 W/mK (vacuum insulation) and to 0.07 W/mK (e.g. packed beds out of expanded spherical glass grains) the solar fraction varies by only ±2% points. Only for very bad insulation properties (0.5 W/mK, e.g. completely destroyed insulation material by moisture or ground water, for which a certain risk is present in an underground installation), the solar fraction clearly decreases, especially at large storage volumes.

The dependency of the solar fraction from the thermal conductivity is far more pronounced in a standard

Task 32 system. One reason for the rather low influence shown in Fig. 3.5 is the interaction between the tank and the surrounding ground. Another reason is the storage concept as discussed above, which leads to a rather low solar fraction in winter time.

4. Conclusion

A new hot water storage was developed to enlarge the solar fraction of single and multi family houses, which consists in a buried concrete cistern, which is insulated at the inner side with a new insulation foam material based on XPS. The storage prototypes with a water volume of about 5 m³ reached heat loss coefficients of about 5 W/K. Two different expansion concepts have been tested, whereat the concept with air volume above the water, which is communicating with the ambient air, has been proved to be more convenient. The concept has proved to work properly; the materials tested did not show significant changes.

In order to simulate the tank including its surrounding soil, a mathematical model was developed, implemented and tested in TRNSYS and connected to the Type 340 (Multiport Store-Model). Simulations carried out with this new type, basing on a system concept, where the complete amount of solar yield is directed via the storage tank, show rather low solar fraction values, mainly caused by the necessary utilization of internal heat exchangers. Concept improvements are on the way. Furthermore, a rather low dependency of the solar fraction on the storage volume has been found in this system concept: Only a decrease of 2 percental points in solar fraction has been stated, if one third of the optimum volume (maximum solar fraction) is installed.

5. Nomenclature

Symbol	Quantity	Unit
Q	Heat flow	W
η	Efficiency factor	-
W	Electricity	W

Subscripts

boiler	auxiliary boiler
ref	Value or parameter of the reference system
el	Electrical
penalty	to account the effects of loss of comfort (DHW & heating)

6. References

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