THERMOSYPHON SOLAR HOT WATER HEATER DEVELOPMENT

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1. Introduction

Thermosyphon solar hot water systems have been a subject to R&D activities of the *CENTRE OF EXCELLENCE FOR RENEWABLE ENERGY RESEARCH* at Ingolstadt University of Applied Sciences since 2004. After building up a test rig, several thermosyphon systems were tested according to ISO 9459-2 (ISO 1995). Additionally, tests procedures developed at Ingolstadt University have been carried out in order to learn more about the systems´ behaviour under special conditions, e.g. its stagnation behaviour. In the end of 2007, a R&D project was started at the *CENTRE OF EXCELLENCE FOR RENEWABLE ENERGY RESEARCH*. Objective of the project is the development of an optimised thermosyphon solar hot water heater based on a scientific R&D procedure. A market analysis shows that most thermosyphon systems are still developed by trial and error (Brandmayr and Zörner 2007). This project, however, aims at demonstrating a closed development cycle. The initial steps include the analysis of thermosyphon systems in theory and the transfer of the mathematical model into simulation. The impact of various system parameters on the overall system performance is simulated in a sensitivity analysis. The results, leading to a fictive optimised thermosyphon system are transferred into a system prototype, which is thoroughly tested at the university`s solar-thermal laboratories. The measurement results are used to optimise the prototype and to achieve validation of the simulation model. The optimised prototype system is prepared for mass production by the industrial project partner.

2. Investigated System Size

Two different system dimensions are available on the market. On the one hand, there are systems with about 2 m² of collector area and approximately 150…180 l of hot water storage for households consisting of two to four persons. This dimension is the basis of the development. Especially Central European manufacturers, which are confronted with saturated local markets, try to enter the Southern European markets with this system size. As collectors developed for Central European demands are generally over-engineered for southern demands, such thermosyphon hot water heaters tend to overheat during summer times. In contrast to this, a well engineered state-of-the-art system is able to cover up to 70 % of the annual hot water demand.

On the other hand, there are systems available with about 300 l of storage volume and a collector area of about 4 m², which meet the requirements of a 4-6 person household.

3. System Simulation

The Matlab/Simulink based CARNOT blockset (Conventional And Renewable eNergy systems Optimization Toolbox) (Hafner et al. 1999) is used as simulation environment for the thermosyphon system optimisation. CARNOT is a tool for the calculation and simulation of heating system components with regard to conventional and regenerative elements. It provides models for heat sources, storage systems, hydraulics and fundamental material calculation as well as the possibility of integrating further models. In order to achieve realistic system behaviour, CARNOT was enhanced by a model of a double mantle heat exchanger storage (Brandmayr et al. 2008) which is commonly used within modern thermosyphon systems.

In general, the thermosyphon simulation models consist of the solar collector, the double mantle heat exchanger storage tank, the interconnecting pipes and a so called thermosyphonic pump. The thermosyphonic pump is a block calculating the mass flow from pressure differences in the hydraulic circuit (Figure 1).

All blocks in the system are connected via data vectors according to their position in the system. The most important vector is the thermo hydraulic vector (THV), in which all relevant values are bundled. It includes the fluid identity, e.g. water or water-glycol mixture, fluid pressure, pressure drop (calculated in the block before), fluid temperature and density. Due to this THV, realistic system behaviour can be achieved. All relevant data to the system design are stored in steps of 5 min to the workspace. These data are automatically evaluated after every simulation run.

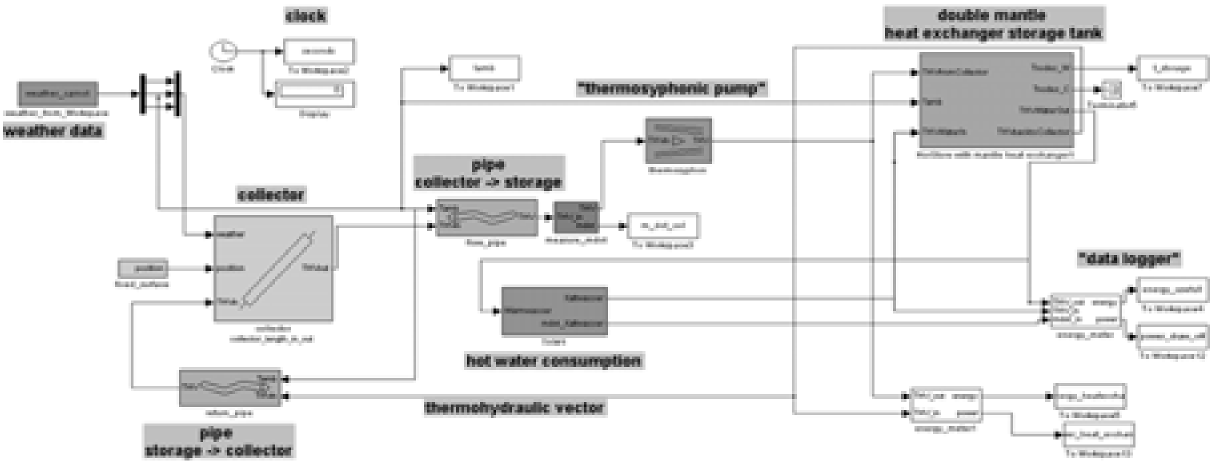

Fig. 1. CARNOT Thermosyphon System Model.

In the following, the simulation model was approved using measurement data of different thermosyphon systems, which were investigated at the *Centre of Excellence for Renewable Energy Research*. Besides single day simulation runs, a comparison of the annual energy output taking on the one hand data predicted according to ISO 9459-2 and on the other hand simulation results into account was carried out. The deviation of the results was found to be 2...5 % for both simulated locations – Ingolstadt and Rome. Due to its more advanced time-variable calculation method, the CARNOT simulation returns always the lower annual energy output.

4. Sensitivity Analysis

Reference of the sensitivity analysis is a thermosyphon system consisting of a flat-plate collector with around 1.9 m² aperture area and a 180 l double mantle heat exchanger storage tank (Table 1).

Tab. 1. Technical Characteristics of the Measured and Simulated Thermosyphon System.

Collector aperture area	1.89 m²
Collector cover material	Prismatic tempered glass, 3.2mm thickness
Collector hydraulics	Diameter header: 18x1mm; diameter riser: 8x0.5 mm; number of risers: 10
Collector slope	38 °
Heat transfer fluid	Water
Storage	Horizontal double mantle heat exchanger storage, volume: 180 l , diameter: 0.48 m, length: 1.46 m
Tank insulation	30 mm polyurethane
Heat exchanger	Double mantle, volume: 8.5 l
Connecting pipes	Well insulated tube, 22x1 mm, total length: 2.64 m
Location	Ingolstadt, Germany

Typically, a heating rod is included in the storage tank to maintain a high hot water comfort even in times of adverse weather. Due to its negative influence on the annual solar fraction, the heating rod is not modelled. To fully cover the hot water demand, a continuous-flow water heater is joined to the thermosyphon system. The flow heater only has to cover the temperature gap between storage tank outlet and 45 °C. For sunny periods with storage tank temperatures above 45 °C, a thermostatic mixing valve is included to reduce the tap water temperature to the desired temperature of 45 °C. Such system setup is commercially available and corresponds to the state-of-the-art of modern thermosyphon systems (figure 2).

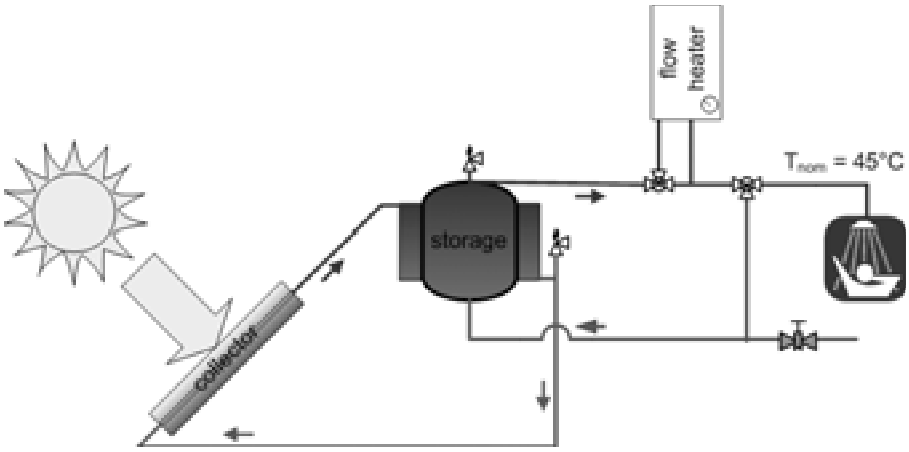

Fig. 2. Operating Scheme of the Investigated Thermosyphon System with Flow Heater and Thermostatic Mixing Valve.

Adapted to common simulation tools, the simulated daily hot water demand corresponds to a 3...4 person household and has a total amount of 2,540 $kWh \cdot a^{-1}$. During the day, three draw-offs take place, in the morning, during midday and in the evening. Additionally, seasonal variations taking a reduced hot water demand during summer times into account are considered.

Considering the system dimension and the users' hot water demand, the aim of the sensitivity analysis is to determine the overall performance defined as a function of collector design, storage tank design and system configuration as shown in equation 1.

$$\eta_{system} = f(collector_{fictive}, storage_{fictive}, configuration_{fictive}) \quad \text{(eq. 1)}$$

Breaking down each of the three sub functions, 18 directly influencing design parameters are found and investigated in a number of simulation runs. In addition, 3 locations with different climatic conditions, Ingolstadt (D), Rome (I) and Malaga (E) are simulated with each of the design parameter sets in order to determine the influence of the weather on the technical system design.

4.1 Target Parameters

Within the scope of the collector optimisation, the significant absorber design parameters (pressure drop, absorber efficiency and heat capacity), the optical properties (transmission-absorption product, incidence angle modifier), the heat losses as well as geometric dimensions (aperture area and length/width ratio) are varied in the simulation runs.

Regarding the storage tank, four relevant parameters are found: the storage tank volume (absolute and relative to the collector aperture area), the characteristics of the heat exchanger (heat exchanger type, position and surface area), the insulation (material and thickness) and the storage tank material.

Besides the two major components of a thermosyphon system – the solar collector and the storage tank – the system configuration strongly influences the energetic performance and the aesthetic appearance. The energetic performance is affected by the pipe dimensioning (length and diameter), the height ratio between collector and storage tank as well as the system orientation – collector azimuth and incidence slope.

4.2 Simulation Results

Based on the annual energy output of the thermosyphon system, the results of the sensitivity analysis are interpreted. A detailed investigation in steps of a few minutes is also possible and in some cases necessary, e.g. an extensive analysis of the collector pressure drop. A fact that has to be emphasised is that most of the optimum values are independent of the respective geographic location. Table 2 shows the weighted classification of the simulation results. The first column describes the varied parameter, the second column identifies either the directly or indirectly affected component. The results concerning the solar collector are discussed in detail in the following chapters with their influence on the prototype design. By combining the results to a most promising system setup, an annual solar fraction of 80 % can be achieved. This fictive prototype differs from the state-of-the-art as the aperture area is about 2.5 m² and the storage tank volume is decreased to 165 l.

Tab. 2: Simulation Results of the Sensitivity Analysis.

Parameter	Component	Influence
Aperture Area	Collector	each > 10 %
Pipe Insulation	System	
Optical Efficiency	Collector	
Collector Tilt Angle	System	
Storage Insulation	Storage Tank	
Incidence Angle Modifier	Collector	
Pipe Diameter	System	each 5...10 %
Height Difference Collector Storage	System	
Linear Heat Loss Coefficient	Collector	
Quadratic Pressure Drop Coefficient	Collector	
Collector Length (at given area)	Collector	each 0...5%
Storage Volume	Storage Tank	
Storage Tank Diameter (at 180 l)	Storage Tank	
Heat Exchanger Area	Storage Tank	
Linear Pressure Drop Coefficient	Collector	
Heat Capacity Collector	Collector	
Quadratic Heat Loss Coefficient	Collector	
Heat Carrier Volume	Storage Tank	

5. Collector Prototype

The collector prototype is designed according to the results of the sensitivity analysis with a regard to cost reduction potentials.

5.1 Production Cost Structure of Flat-Plate Collectors and Cost Reduction Potential

Mangold (1996) conducted a detailed investigation concerning collector production cost. This survey was approved by Treikauskas (2009) to be transferrable to today´s collector production. The collector production cost show a big potential for cost reduction on the absorber side. By changing the normally used absorber material from copper to 100 % aluminium, there is the further possibility to reduce the absorber weight in the range of 2.0...3.0 kg for a 2.5 m² collector. Bigger wall thicknesses of the piping and a 0.5 mm thick absorber plate for the aluminium type are considered. Besides that, the raw material prices of aluminium are only 30...40 % of those of copper.

The simulation results also show the possibility of using only 30 mm of backside insulation instead of 40...50 mm as usually included in central European solar collectors. Additionally, there is no need for an insulation of the casing. The impact of the insulation on the production cost is rather low, approximately 9 % of the whole collector costs, but directly affects the minimum height of the collector casing. The height of the collector can be reduced by up to 20 mm resulting in a weight advantage of 2...4 kg depending on the profile geometry and resulting in a cost reduction, too.

5.2 Collector Properties

The most sensitive part of the collector is the absorber and its aperture area. Within the simulation runs it is varied from 0.5…5.6 m². Independent of the simulated geographic location, a secure system operation, meaning a maximum storage tank temperature below 90 °C, is possible up to 2.5 m² collector area. Furthermore, the analysis clearly shows the necessity of a good optical efficiency in the range of 80 %. This can be achieved by using a transparent cover with a transmission value above $\tau = 0.9$ such as low iron glass. A long term stable polymer cover such as PMMA (Frei 1998) with a transmission of $\tau = 0.84$ is not recommended. The other factor which is directly linked with the optical efficiency is the used absorber coating. The coating must have an absorption value of about α = 0.95. An analysis of the collector´s operating regime through simulation and on the testing rig reveals a peak around the optical efficiency of the collector with minor thermal losses (Figure 3). This peak is calculated using the reduced collector temperature as basis (Eq. 2).

$$T_{red} = \frac{\frac{(T_{col,out} + T_{col,in})}{2} - T_{amb}}{G} \quad \text{(eq. 2)}$$

The reduced collector temperature is usually used in collector certificates to achieve a comparability of measurement results for different collectors.

If the collector efficiency curve of a typical selective coated flat-plate collector is included to Figure 3, it can be seen that the thermal losses of the collector in thermosyphon systems are not that important. The simulation results of different coatings from highly selective materials to solar painting lead to the use of a medium selective coating material like black chrome with a typical emission coefficient of about ε = 0.15.

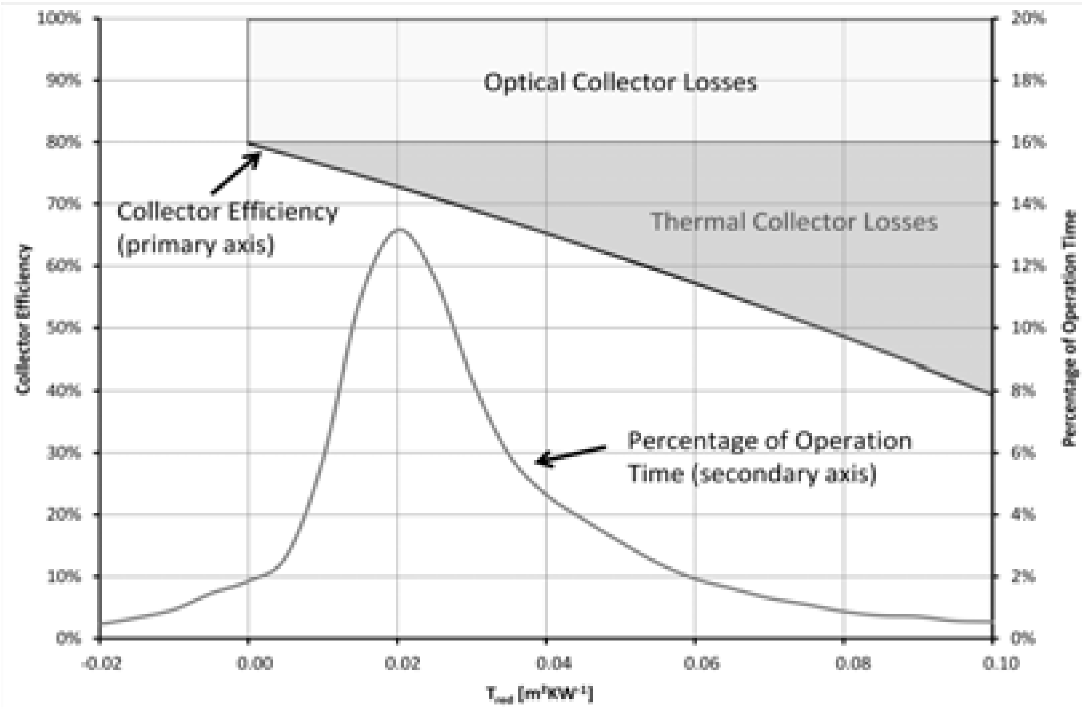

Fig. 3. Collector Efficiency vs. Percentage of Operation Time.

Besides the cover and the coating, the insulation of the collector (ref. Table 2 "Linear heat loss coefficient") has a medium influence on the system efficiency. Therefore, a back side insulation thickness of 30 mm is fully sufficient for collectors used within thermosyphon systems.

The collector capacity, affected by the materials used and above all by the fluid inside the absorber has nearly no influence on the system's annual energy output. A small capacity often correlates with a reduced material usage in the collector and a quick reaction to alternating weather conditions. On the other hand, the material used for the absorber piping can only be reduced to a certain extent as a material reduction comes along with reduced pipe diameters. A small pipe diameter leads to higher pressure losses inside the collector and, therefore, to a reduced mass flow rate in the system. With regard to this material reduction potential and the annual energy output, the pressure drop was simulated ranging from header-riser absorbers to meander type absorbers. The results show nearly no differences between both collector types. Thus, the question arises whether meander-type collectors may also be suitable for thermosyphon systems. A detailed post processing of the simulation results at cloudy conditions shows very small mass flow rates of only 10...14 $kg \cdot h^{-1}$ at a temperature difference of 60...70 °C for the meander-type absorber. This leads to a highly stratified storage tank and thus to no energetic drawback compared to the header-riser absorber system. The flow rate of the header-riser absorber at the same conditions is within the range of 35...45 $kg \cdot h^{-1}$ with a typical temperature rise of 20...30 °C. Especially in summer times with an irradiation into the collector plane of above 1,000 W·m^{-2}, the meander type collector tends to overheat. Temperatures at the collector outlet reach 100…120 °C. This behaviour is verified using the institute´s solar simulator. The technical data for the prototype collector are summarised in Table 2.

Tab. 3: Technical Data of the Proposed Collector.

Absorber Type	Sheet-Pipe
Absorber Material	100 % Aluminium (Absorber and Piping)
Aperture Area	2.5 m²
Insulation	30 mm Mineral Wool
Glazing	Heat Strenghthened Low Iron Glass
Coating	Selective Coating

5.3 Collector Efficiency Measurement

The efficiency curve of the collector prototype is analyzed using the solar simulator according to DIN EN 12975-2 (2006). The characteristics of the efficiency curve shown in figure 4 are comparable to those of collectors used in pumped systems.

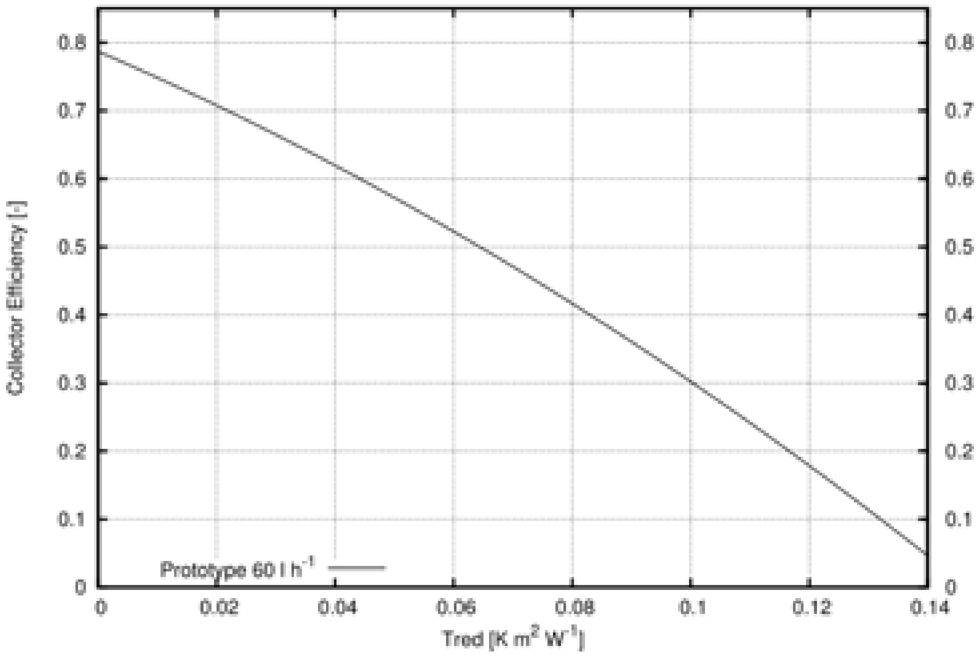

Fig. 4: Collector Efficiency Curve

As the optical collector efficiency is below the estimated goal of 80 % the absorber is checked in detail.

Using infrared thermography, optimisation potential in the flow distribution especially at low flow rates are identified. The correlated redesign of the absorber hydraulic allows implementing further improvements of the collector efficiency factor F'. A second prototype collector is prepared for the efficiency tests in autumn 2011.

6. Storage Tank Development

According to the simulation results, the tap water volume of the storage tank is fixed to 165 l. To increase the hot water comfort, the cold water from mains is piped into the storage tank using a diffuser. Several diffuser shapes are analysed using computational fluid dynamics (CFD) and tested afterwards at the institute. The simulation and measurement results show a very good correlation.

The boundary conditions for the tests are a fully mixed storage tank of approximately 65 °C, a cold water temperature of 20 °C and a draw-off volume flow of 600 ± 25 l·h^{-1}. As long as the tank draw-off temperature does not drop more than 2 °C, the storage tank is considered to be stratified.

An ideally stratified storage remains at its initial temperature until 100 % of its volume is drawn. Afterwards the temperature drops directly to the tap water temperature.

The tests are carried out with heat carrier fluid in the double mantle at tank temperature (approx. 65 °C). This scenario corresponds to real systems. The double mantle volume enlarges the draw-off volume considered to be fully stratified towards 100 %.

Most double mantle heat exchanger storage tanks investigated in Ingolstadt are equipped with simple baffle plates. They are only stratified in the range of 40...60 % of their nominal volume. The prototype reaches a stratification of 95 % comparable to the reference system (figure 4). The main difference between both systems is the diffuser shape. The reference storage uses an injection moulded diffuser, while the prototype uses a low-cost simple pipe structure with defined flow channels.

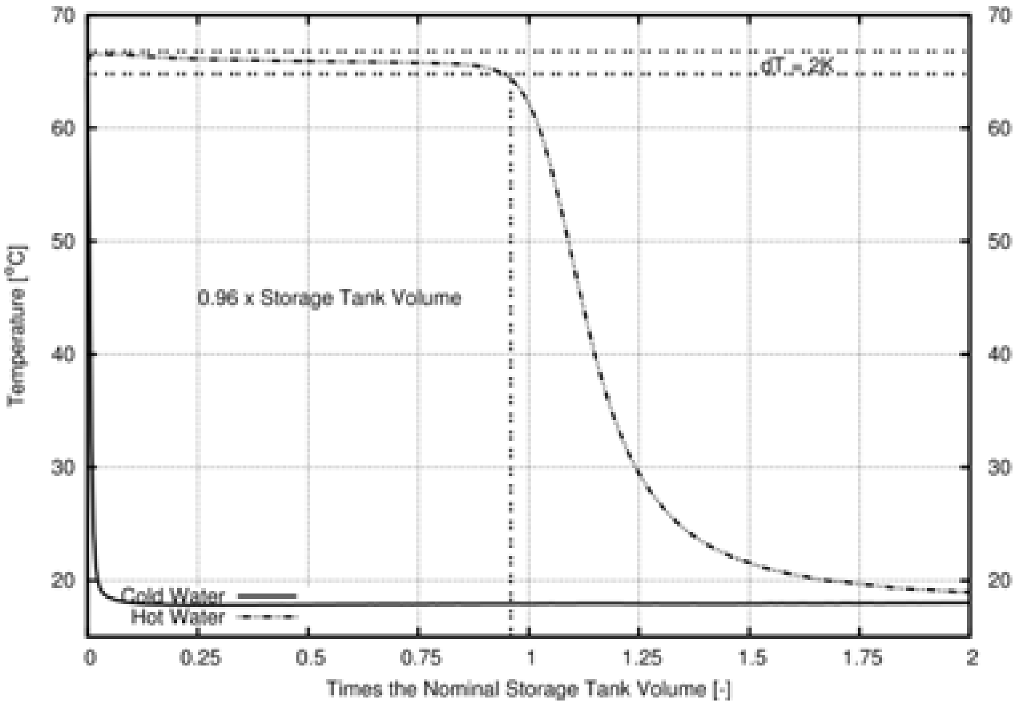

Fig. 4: Test Results Using an Optimised Inlet Diffusor

Two tests are carried out regarding the heat exchanger. To reduce the pressure increase due to temperature related volume expansion in the collector circuit, an expansion vessel is directly integrated into the storage tank. This vessel can cope with a volume expansion up to 3 l and keeps the system pressure below the safety valve opening pressure of 2.5 bar_{abs}. The functionality of the vessel was proved in laboratory tests.

As the pressure drop of the heat carrier circuit directly influences the system performance, pressure drop measurements of all parts are necessary. Compared to the reference storage, the prototype shows a slightly higher pressure drop in the relevant volume flow range of 0...65 $l \cdot h^{-1}$ (figure 5). A detailed analysis of the pressure drop shows manufacturing related optimization possibilities resulting in a lower overall pressure drop.

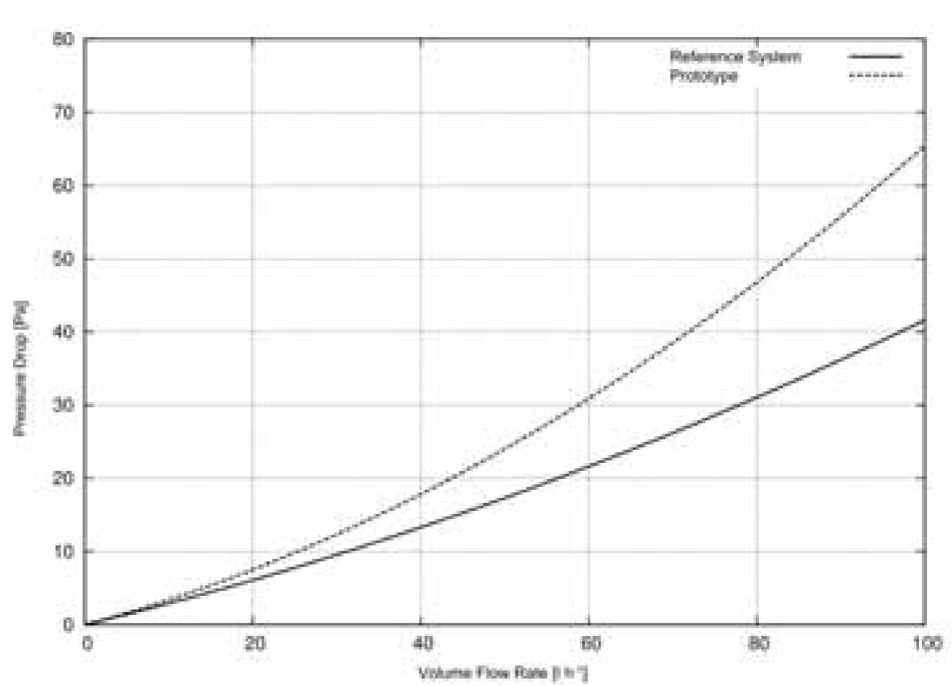

Fig. 5: Pressure Drop of the Double Mantle Heat Exchanger

Table 4 summarizes the technical data of the storage tank prototype.

Tab. 4: Technical Data of the Storage Tank Prototype

Nominal Volume	165 l
Heat Exchanger Volume	7.7 l
Material	Enamelled Steel
Heat Exchanger	Double Mantle, approx. 1 m²
Circuit Points	Collector and Water Connectors at the Bottom
Insulation	30 mm PU-Foam
Width incl. Insulation	1,100 mm
Diameter	600 mm

7. Conclusions

The proposed closed development cycle allows a target-oriented development of solar-thermal applications. Using simulation tools in the design stage of solar-thermal applications enables the identification of the most design driving factors by a parameter variation. The simulation results are directly linked to the design of a specific system component. Often this link is rather indirect or affects more than one part of the system. In such a case, a preliminary mathematical system description is indispensible to the comprehension of the system's dependencies. The overall results of the sensitivity analysis allow designing an optimised thermosyphon system with regard to a maximised solar fraction and a secure operation mode throughout the year. After constructing the parts, every part has to be tested under specific conditions for further optimization possibilities. By applying these technical capabilities, further system improvement is possible.

In the last step of this development project, the whole prototype will be tested ISO 9459-2 (1995). The test results will be compared to the simulation results and be used for model validation.

8. Acknowledgements

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9. Nomenclature

G	$[Wm^{-2}]$	Irradiation in the Collector Plane
T_{amb}	$[°C]$	Ambient Temperature
$T_{col,in}$	$[°C]$	Collector Inlet Temperature
$T_{col,out}$	$[°C]$	Collector Outlet Temperature
T_{red}	$[m^2KW^{-1}]$	Reduced Collector Temperature
η_{system}	[-]	System Efficiency

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