Thermosyphon Systems: Sensitivity Analysis Regarding Optimum Energetic Performance and Cost Effectiveness

Sebastian Brandmayr[1*], Christoph Trinkl[1], Wilfried Zörner[1] and Vic Hanby[2]

[1] *Centre of Excellence for Renewable Energy Research*, Ingolstadt University of Applied Sciences,
Esplanade 10, 85049 Ingolstadt, Germany

[2] Institute of Energy and Sustainable Development at De Montfort University,
LE 1 9BH, Leicester, United Kingdom

[*] Corresponding Author, sebastian.brandmayr@haw-ingolstadt.de

Abstract

In the past, thermosyphon systems have not been part of development and market activities of most central European manufacturers. Nowadays, these manufacturers are confronted with more and more saturated local markets. Hence, these industries are looking for possibilities in export, mainly in the regions around the Mediterranean Basin. In these regions thermosyphon systems correspond to the customers´ demand in an ideal manner because the purchase costs are moderate and the daily production of hot water is sufficient.

A research project of the *Centre of Excellence for Renewable Energy Research* aims at the development of an optimised thermosyphon solar hot water heater with respect to performance and cost effectiveness.

In addition to measurement data collected on the institute’s thermosyphon system test stand, a detailed simulation model was developed to identify the most important design driving parameters. This simulation resulted in optimised thermosyphon system designs related to the respective location – Ingolstadt (D), Rome (I) and Malaga (E). According to the simulation the collector was designed and constructed so far. The other parts of the system will be handled the same way. Especially the material selection, the insulation thickness and the casing height bring along a cost reduction potential without any energetic drawback.

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 the specifications given in ISO 9459-2 [1]. In addition to that, tests according to methods and procedures developed at Ingolstadt University have been carried out in order to learn more about such system’s behaviour under special conditions, e.g. its stagnation behaviour.

In the end of 2007, a R&D project was started which aims at the development of an optimised thermosyphon system based on scientific results. A market analysis carried out beforehand shows that most thermosyphon systems are still developed through trial and error [2]. This project, however, aims at demonstrating a closed development cycle. This cycle includes the analysis of thermosyphon systems in theory, the transfer of the mathematical model into simulation, the design of a prototype based on the simulation results and, eventually, the testing of the prototype in order to maximize the system performance and to achieve validation of the simulation model. This validated system model is going to offer the project partner, a manufacturer of solar-thermal applications, the possibility of adapting their thermosyphon systems to customers and climatic conditions.

2. Simulation Environment

The Matlab/Simulink based CARNOT blockset (Conventional And Renewable eNergy systems Optimization Toolbox [3]) is used as simulation environment for the thermosyphon system optimisation. CARNOT is a tool for the calculation and simulation of the thermal components of heating systems 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 [4] which is commonly used within modern thermosyphon systems.

3. System Simulation

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 a mass flow from the 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.

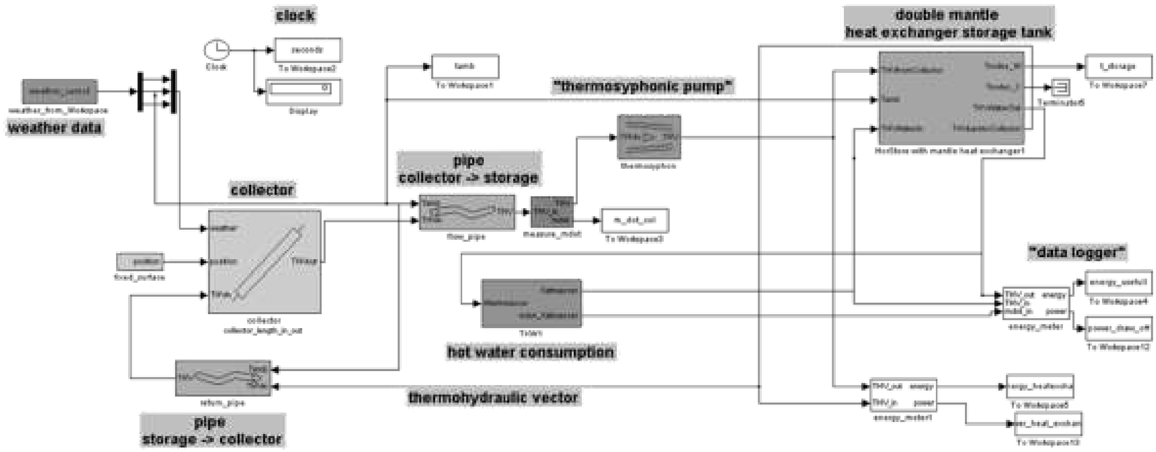

Fig. 1. CARNOT Thermosyphon System Model.

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 [1] and on the other hand simulation results into account was carried out. The deviation of the results was found to be between 2…5 % for both simulated locations – Ingolstadt and Rome. The CARNOT simulation returns always the lower annual energy output, which is due to its more advanced time-variable calculation method.

4. Sensitivity Analysis

Reference to 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.
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 of the thermosyphon system, 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 in order 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).

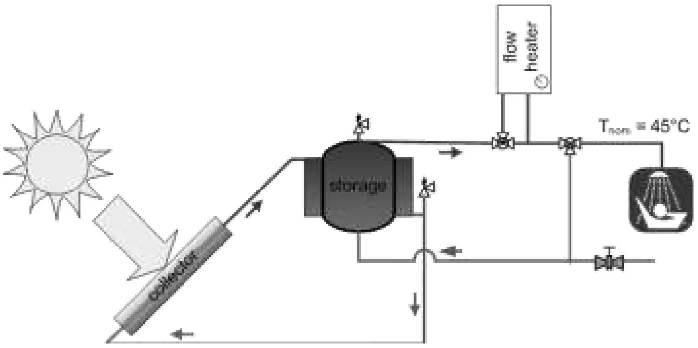

Fig. 2. Operating Scheme of the Investigated Thermosyphon System with Flow Heater and Thermostatic Mixing Valve.

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·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.

Taking the system dimension and the users' hot water demand into account, 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 2-1:

$$\eta_{system} = f(collector_{fictive}, storage_{fictive}, configuration_{fictive}) \tag{4-1}$$

Breaking down each of the three sub functions, 18 directly influencing system design parameters were found and simulated.
In addition, 3 locations with different climatic conditions are simulated with each of the design parameter sets in order to determine the influence of the weather on the technical system design. The results of the simulation study are combined to an optimised fictive design of a thermosyphon system and finally transferred into a system prototype which will be tested on the institute's testing rig.

4.1. Climatic Conditions

According to the geographic/climatic conditions, thermosyphon systems have to be operated using different water/antifreeze mixing ratios. A low antifreeze ratio has a positive influence on the energetic/hydraulic behaviour of the solar-thermal system. Therefore, the sensitivity analysis is carried out using three climatic different European locations, i.e. three different working fluids:

- Ingolstadt, Germany, is included as northernmost location with typical central European weather conditions. The institute´s testing rig is located there, which will be used to carry out measurements with the prototype. The working fluid used for this location is a 60/40 water/propylene glycol mixture which allows ambient temperatures of about -15 °C in winter.
- Rome, Italy, is a location with a moderate southern European climate. Even in winter times there are only very few days with frost. Therefore, a 90/10 water/propylene glycol mixture is sufficient for a safe system operation throughout the year.
- Malaga, Spain, has a typical southern European climate – high amount of solar irradiation at high average temperatures without a real risk of frost. Therefore, no antifreeze protection is needed. In order to protect the thermosyphon system, it is recommended to run the system with corrosion protection.

4.2. 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 and simulated.
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 has a high influence on the energetic performance and the aesthetic appearance. The energetic performance is affected by the pipe dimensioning (length and diameter), its piping between storage tank and solar collector, the height ratio between collector and storage tank as well as the system orientation – collector azimuth and incidence slope.

4.3. Simulation Results

Based on the annual energy output of the thermosyphon system, the results of the sensitivity analysis are interpreted. Besides this interpretation a detailed investigation in steps of 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 1 shows the weighted classification of the simulation results. The first column shows the varied parameter, the second column identifies the either 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.

Table 1. 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. Production Cost Structure of Flat-Plate Collectors and Cost Reduction Potential

Mangold [5] conducted a detailed investigation concerning collector production costs. This survey was approved by Treikauskas [6] to be transferrable on a modern collector production. The collector production costs 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 2.5…3.0 kg for a 2.5 m² collector. Bigger wall thicknesses for the piping and a 0.5 mm thick absorber plate for the aluminium type are considered. Besides that, the raw material prices for aluminium are only 30…40 % of those for copper.

Moving away from the absorber, the simulation results show the possibility of using only 30 mm 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 costs 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 coming along with a weight advantage of 2…4 kg depending on the profile geometry and its correlated cost reduction.

6. Development of a Collector Prototype

The collector prototype is designed according to the results of the sensitivity analysis with a regard to the mentioned cost reduction potentials. The most sensitive part of the collector is the absorber and its aperture area. Within the simulation runs it was 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.
Moving away from the absorber’s geometrical dimensions, the analysis clearly shows the necessity of a good optical efficiency in the range of > 80 %. This can be reached 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 [7] 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 $\alpha = 0.95$. An analysis of the collectors’ operating regime within 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 (Eqn. 6-1).

$$T_{red} = \frac{\frac{(T_{col,out} + T_{col,in})}{2} - T_{amb}}{G} \qquad (6\text{-}1)$$

The reduced collector temperature is usually used in collector certificates in order to achieve 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 down to solar painting lead to the use of a medium selective coating material like black chrome with a typical emission coefficient of about $\varepsilon = 0.15$.

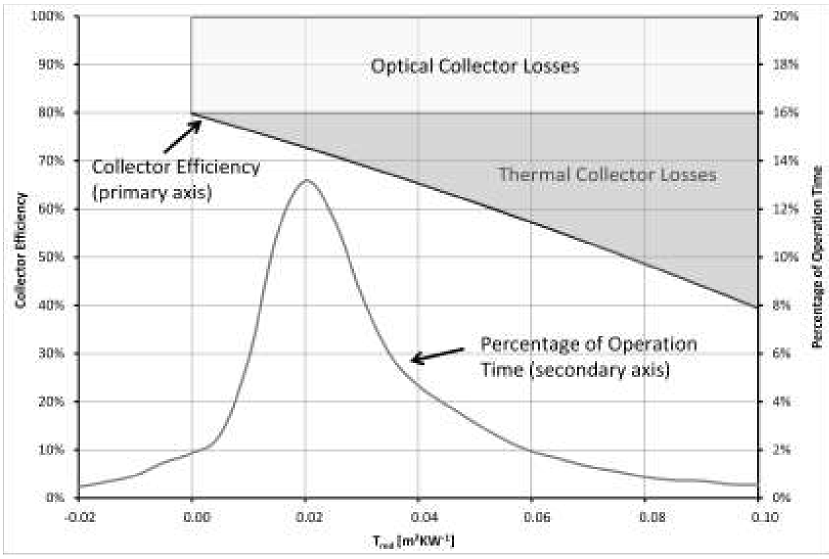

Fig. 3. Collector Efficiency vs. Percentage of Operation Time.

Besides the cover and the coating the insulation of the collector (ref. Table 1 "Linear heat loss coefficient") has a medium influence on the system efficiency. Therefore, an insulation thickness of 30 mm only on the back side is fully suitable 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 comes along with a reduced material usage in the collector and a fast 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 and, therefore, the question arose if meander-type collectors might 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·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·h^{-1} with a typical temperature rise of 20…30 °C. Especially in summer times with irradiation values into the collector plane of above 1,000 W·m^{-2}, the meander type collector tends to overheat as temperatures at the collector outlet reach 100…120 °C. This behaviour could be verified using the institute´s solar simulator. The technical data for the proposed collector are summarised in Table 2.

Table 2. 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 Strengthened Low Iron Glass
Coating	Selective Coating

7. Conclusion

Using simulation tools in the design stage of solar-thermal applications allows the identification the most design driving factors by a parameter variation. Target of the simulation was to be able to directly link the simulation results to the design of a component in the system. Often this link is rather indirect or affects more than one part of the system. In such 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.

The collector prototype has already been constructed according to the proportions out of the simulation. It will be tested under the solar simulator in order to determine its efficiency curve. Additionally the pressure drop curve will be measured and transferred into simulation.

The procedure for storage tank and system design is going to be the same way.

After constructing the system prototype, it will be tested on the university's testing rig according to procedures given in international standards. Additionally, the stagnation behaviour will be analysed in detail. After conducting the part and system characterisation the simulation model will be approved. Afterwards the simulation model can be used for the adaption of the system to other climatic conditions or a completely differing hot water demand.

8. Acknowledgement

This research project is carried out in cooperation with *CitrinSolar Energie und Umweltechnik GmbH*, a German manufacturer of solar-thermal components and systems. The project is financially supported by *Deutsche Bundesstiftung Umwelt* (DBU), one of Europe's largest foundations promoting innovative and exemplary environmental projects.

Nomenclature

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

References

[1] ISO 9459-2 (1995). Test Methods for Solar Collectors – Part 2: Outdoor Test Methods for System Performance Characterization and Yearly Performance Prediction of Solar-only Systems, ISO, Switzerland.

[2] S. Brandmayr, W. Zörner (2007). Thermosyphon Systems: Market, State-of-the-Art and Trends, 3rd European Solar Thermal Energy Conference (estec2007), Freiburg (Germany), June 2007, p. 182 – 188.

[3] B. Hafner, J. Plettner, C. Wemhöner (1999). CARNOT Blockset: Conventional And Renewable eNergy systems OpTimization Blockset – User's Guide, Solar-Institut Jülich, Aachen University of Applied Sciences (Germany).

[4] S. Brandmayr, M. Konrad et al. (2008). Simulation of Thermosyphon Solar Hot Water Systems Using Matlab/Simulink and Carnot, Eurosun 2008 – 1st International Conference on Solar Heating, Cooling and Buildings, Lisbon (Portugal), October 2008, p. 546-547.

[5] D. Mangold (1996). Kostenanalyse der Herstellung von Solarkollektoren und mögliche Kostenreduktionen durch Massenfertigung, 6. Symposium Thermische Solarenergie, Bad Staffelstein (Germany), May 1996, p. 330 – 334.

[6] F.-D. Treikauskas (2009). Development of a volumetric solar thermal absorber, PhD, De Monfort University, Leicester (United Kingdom).

[7] U. Frei (1998). Kollektoren in Solarthermischen Systemen, In: 1998 TRISOLAR. Bregenz (Austria), February 1998, Available at: http://www.solarenergy.ch/publ/kollektoren/trisolar.pdf [Accessed: 5 January 2009].