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Heat Pipe Collectors for Cost Reduction of Solar Installations

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Abstract

Heat pipes in solar thermal collectors offer the advantage of a simpler hydraulic interconnection of the solar circuit while reducing the system load during stagnation compared to direct flow collectors. Within a research project, we basically analyzed heat pipe solutions for collectors, developed design methods and optimization potential and investigated the integration of heat pipes in flat plate collectors. Novel flat plate collector prototypes with an inherent overheating protection have been built and tested successfully. The maximum fluid temperature was limited to 140 °C, thus compared to a direct flow collector, a temperature decrease of more than 40 K is achieved. This paper presents the developed technology and explains, that the transfer of complexity from the system to the collector by the use of heat pipes can lead to a reduction of system costs of more than 25 %.

Key words: *heat pipe, flat plate collector, cost reduction, stagnation temperature, aluminum heat pipe*

1. Introduction

Compared to direct flow collectors, the use of heat pipes in collectors offers the advantage of a simpler hydraulic interconnection of the solar circuit resulting in a reduced pressure drop and a reduced system load during stagnation. Thus, the use of heat pipes can lead to simpler and more reliable solar thermal systems. The optimization potential of the technology and thus the potential benefits, however, are not maxed out or even unknown. Within the research project “Heat pipes in solar collectors - principles of thermodynamics, evaluation and new approaches for integration”, the heat transfer characteristics of heat pipes and manifolds have been evaluated (Jack and Rockendorf, 2013). By means of experimental studies and newly developed theoretical models, novel heat pipe solar collectors have been designed, which can significantly reduce the stagnation temperature in the solar circuit. Finally, a flat plate collector prototype with aluminum heat pipes and inherent overheating protection has been built and tested successfully. Further, the cost reduction potential for the entire system as a consequence of this novel heat pipe collector has been analyzed.

2. Modelling and Optimization of Heat Pipes in Collectors

Within their operating range, heat pipes exhibit a large heat transfer capability, even for small temperature differences due to the phase change of the working fluid. Nevertheless, the thermal resistance and the resulting temperature difference between the evaporator and the condenser of the heat pipe in solar collectors are not negligible. It is important to quantify the heat transfer behavior of the heat pipes and its influence on the collector efficiency as well as to know their operation limits. On the one hand, these limits have to be designed properly to ensure the operation of the collector; on the other hand, the dry out limit can be used to prevent the heat transfer above a certain temperature to reduce the temperature load of the solar circuit in case of stagnation. Figure 1 illustrates the operating range, which is restricted by the heat pipes’ limits of operation.

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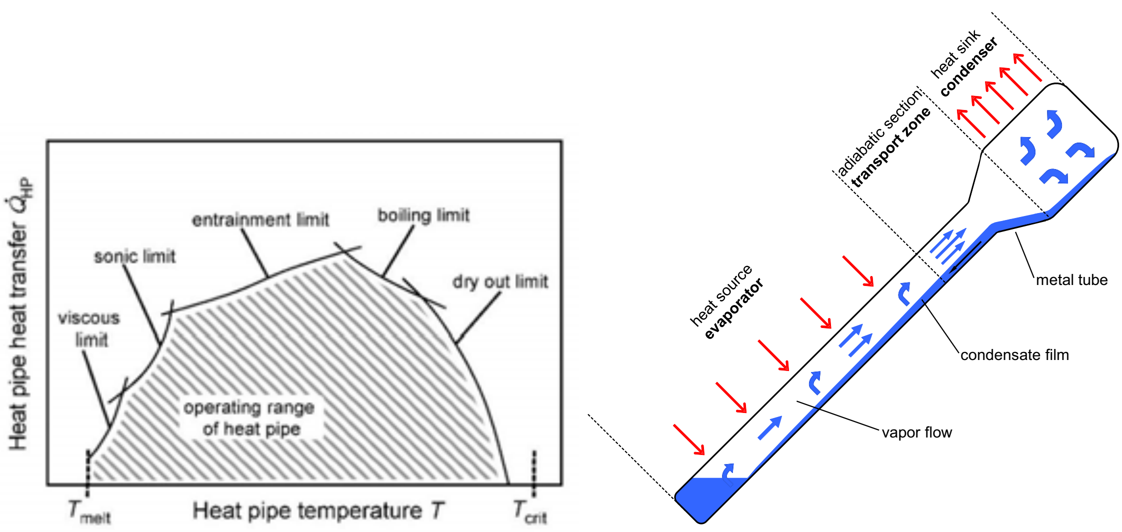

Fig. 1: Reduced operating range of gravitational heat pipes due to melting temperature and critical temperature of the working fluid as well as operation limits (left; Faghri, 1995) and schematic illustration of a gravitational heat pipe for solar collectors (right)

2.1 Modelling

Basic experimental studies have shown that the thermal resistances of the heat pipes and the manifold (thermal connection of the heat pipe condenser to the solar circuit) are similar in magnitude, and thus both components have a relevant influence on the internal heat transfer coefficient U_{int} between absorber and fluid of collectors. In contrast to direct flow evacuated tube collectors (U_{int} between 80 W/m²K and 100 W/m²K), the internal heat transfer coefficient of evacuated tube collectors with heat pipes is between 20 and 50 W/m²K. Thus, the conversion factor η_0 is decreased by one to four percentage points compared to direct flow evacuated tube collectors.

For a deeper understanding of the heat transfer characteristics of the components heat pipe and manifold the individual heat transport phenomena have to be investigated. For this reason we carried out theoretical modelling for both heat pipes and manifolds, which have been validated experimentally. The developed calculation and design methods were used to investigate the heat transfer characteristics in detail, to identify potential for optimization and to design new heat pipes for flat plate collectors. The theoretical models of the heat transfer processes are explained in detail in a previous paper (Jack et al. 2013) as well as in the final report of the project (Jack and Rockendorf, 2013).

2.2 Optimization approaches for heat pipes

We have determined the basic influences of customary heat pipes filled with different media (water and organic fluids) and manifolds on the collector performance, summarized by the following key points:

- The thermal resistance of heat pipes with organic working fluids is much higher than the thermal resistance of heat pipes with water as the working medium.
- In contrast to water, organic working fluids can lead to a stagnation temperature limitation in the collector due to their low dry-out limit.

Thus, with organic working fluids a reduction of the load in the solar circuit in case of stagnation can be achieved. This can lead to significant simplifications of the solar circuit.

In addition, the heat transfer by condensation mainly depends on the thermal conductivity of the working fluid. Thus, further organic working fluids were investigated reduce the thermal resistance compared to existing solutions and to achieve a limitation of the temperature in the collector. We examined different alkanes, alcohols and ketones.

The thermal resistance of heat pipes with alkanes like butane, pentane and hexane are in the range of 0.2 K/W. Calculations show that the resistance with the use of acetone can be reduced by about 40 % and with methanol even by 50 %. Other working fluids with a very high thermal conductivity in comparison to alkanes and alcohols, such as ammonia, are also conceivable. Ammonia, however, was not further investigated, since its critical temperature is relatively low (132 °C) and its vapor pressure is very high, which requires large pipe wall thicknesses.

Besides the theoretical evaluation by means of the developed models, the increase of the condenser surface and the performance of different working fluids have also been assessed by measurement. For this purpose, we manufactured several heat pipe prototypes with acetone and methanol at ISFH. The optimization approaches of the improved heat pipe prototypes have been confirmed by measurement. Our results show that a significantly increased thermal conductance of heat pipes with organic working fluids suitable for stagnation temperature limitation is possible. Compared to commercially available heat pipes the conductance could be increased by a factor of 1.5.

Because of the small dimensions of the condenser in contrast to the evaporator the condensation heat transfer is essential for the heat transfer ability of the gravitational heat pipes for solar collectors. Thus, the increase of the available inner surface of the condenser is a significant approach for optimization. This can be achieved by an increase of the diameter or length of the condenser as well as by enlargement of the inner surface with the same external dimensions, for example by internal ribbing. Experiments showed that doubling of the inner condenser surface increases the overall heat pipe conductance by a factor of 1.7. Hence an enlargement of the inner surface of the condenser reduces the thermal resistance of the heat pipe nearly directly proportional.

Besides the optimization of the heat transfer characteristics of heat pipes, cost optimization potentials have been investigated as well. In addition to minimizing the use of materials, a cost reduction can also be achieved by the choice of the heat pipe material. Typically, heat pipes for solar thermal collectors are made of copper. A substitution of copper with aluminum or stainless steel is also conceivable. The use of aluminum in heat pipes in combination with different working media has been intensively studied (Faghri, 1995, Reay and Kew, 2006). We have developed a laboratory method for manufacturing aluminum heat pipes and demonstrated the reliability and heat transfer capability of the produced heat pipes for use in collectors. The results were presented in a former publication (Jack et al. 2013).

3. Limiting the stagnation temperature by the use of heat pipes

As mentioned, a correct design of the dry out limit of gravitational heat pipes leads to a reduction of the temperature in the solar circuit in case of stagnation. This technology is already used in commercially available evacuated tubes of the German company *NARVA Lichtquellen* using an organic working fluid to limit the stagnation temperature to 160 °C (Mientkewitz, 2010). Typical commercially available heat pipes with water are unsuitable for a stagnation temperature reduction by the use of the dry out limit.

The development goal should be to disable the heat transfer of the heat pipe as close as possible to the upper limit of the operating temperature range of the collector. Thus, the calculation methods for the dry out limit as well as the knowledge of the factors influencing it are essential.

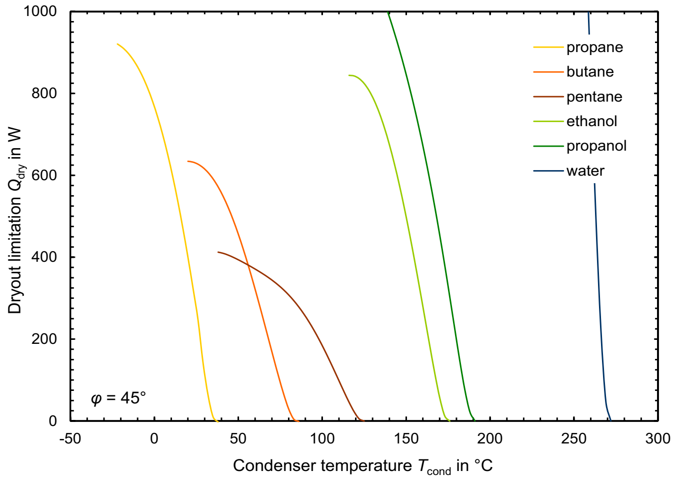

Fig. 2: Calculated dry out limits of gravitational heat pipes for solar thermal collectors filled with different working fluids

For the following discussion, an exemplary heat pipe with an evaporator length of 1.7 m, an inner diameter of the evaporator of 8 mm, a condenser length of 50 mm, a condenser inner diameter of 20 mm filled with a mass of 3 g of the working fluid is defined. Figure 2 shows the dry out limits for the defined standard geometry with different working fluids that have been determined by our newly developed model.

For a fixed mass of working fluid (in this case 3 g) the maximum temperature varies between 35 °C for propane and 270 °C for water. Thus the shutdown temperature can be adjusted over a wide range by the choice of the working medium. However, several working fluids are not suitable for the use in combination with the pipe material due to instability or incompatibility.

The influence of the amount of working fluid on the dry out limit by varying the mass of the working fluid is exemplarily shown in Figure 3 for butane and water. If water is used in the heat pipe with the previously defined standard geometry the dry out temperature may be varied from 170 °C with 0.5 g of water, to 290 °C with 4 g of water. However, for smaller amounts of water the curve of the shutdown shows a smaller slope and the maximum transferable heat flux drops significantly. With a mass of 0.5 g of water the maximum power of the heat pipe is limited to 55 W. Thus, by the use of water no practical temperature limitation can be achieved in the collector using the dry out limit. With butane the influence of the mass of working fluid on the dry out temperature is quite similar, but the overall temperature level is lower.

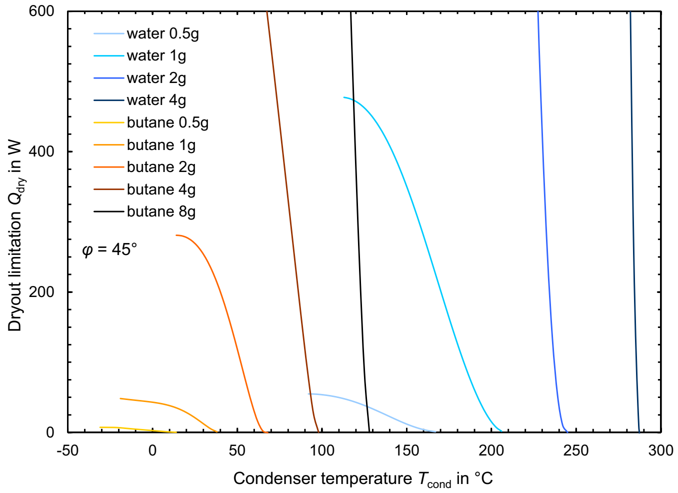

Fig. 3: Calculated dry-out limits of gravitational heat pipes for solar thermal collectors with different types and amounts of working fluids

However, the shut down in the collector does not have to be referred to the evaporator temperature, but to the average fluid temperature of the solar circuit, since this temperature has to be limited in case of stagnation. Thus, the components heat pipe and manifold have to be considered as thermal resistances between the evaporator temperature and the fluid temperature. A reduction of the thermal resistance of both the heat pipe and the manifold increases the slope of the dry-out limit and thus the sharpness of the shutdown.

Figure 4 shows the influence of the thermal resistance of the heat pipe and the manifold on the collector efficiency and on the shutdown function for a standard evacuated tube collector. The default values of the thermal resistances of heat pipe ($1/U_{HP1}$) and manifold ($1/U_{Man1}$) were recognized. The thermal resistances were reduced stepwise for the calculation using the following definition: $1/(U_{HP1} \cdot i) = 1/U_{HP\,i}$ and $1/(U_{Man1} \cdot i) = 1/U_{Man\,i}$.

For the typical thermal resistance of heat pipe and manifold (G = 1000 W/m²) there is a temperature difference of 40 K between the starting of the shut down and the stagnation temperature (η = 0). By reducing the thermal resistance of the heat pipe by a factor of 3, this temperature difference can be reduced to 27 K. If, in addition, the thermal resistance of the manifold is reduced by a factor of 3, there is a temperature difference of only 22 K. Thus, theoretically a significant increase in the sharpness of the shutdown can be achieved and in turn, the stagnation temperature could be further reduced by up to 20 K.

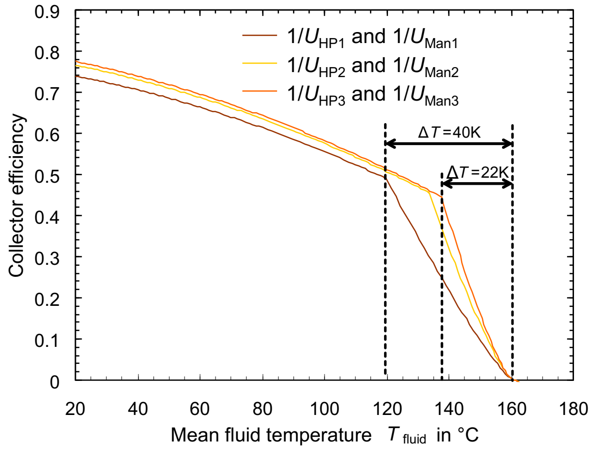

Fig. 4: Calculated influence of the thermal resistances of the heat pipe and the manifold on the collector efficiency and the shut down behaviour of a standard evacuated tube collector with an alkane as working fluid.

This means that the reduction of the thermal resistance of heat pipes as well as the reduction of the thermal resistance of the manifold represent optimization potential not only with regard to performance but also with regard to the shutdown behavior. The thermal resistance of the heat pipe should be as small as possible, since higher resistances lead to a less sharp shut down. Thus, within the investigation regarding optimal working fluids for a certain shutdown temperature the dry out limit and the thermal resistance of the heat pipe and thus the thermal conductivity of the working fluid has to be considered.

4. Flat-plate collectors with deactivating aluminum heat pipes

Based on the developed evaluation and design methods for heat pipes and manifolds we investigated the integration of heat pipes with organic working fluids into flat plate collectors.

Considering the above-mentioned correlations, several solutions of the heat pipe condenser-manifold connections were developed. The design of the heat transfer limits is exemplarily explained in figure 5. On the one hand, the entrainment limit has to be considered in order to design the diameter of the heat pipes as small as possible. For this purpose, the maximum heat transfer rate the heat pipe has to provide at the lowest operating temperature has to be considered (see design point “B1” in figure 5). For the dry out limit, the collector heat gain at the highest operating temperature is crucial, which is represented by the design point B2. The calculation of the dry out limit for this boundary condition then allows to estimate the expected stagnation temperature represented by point B3.

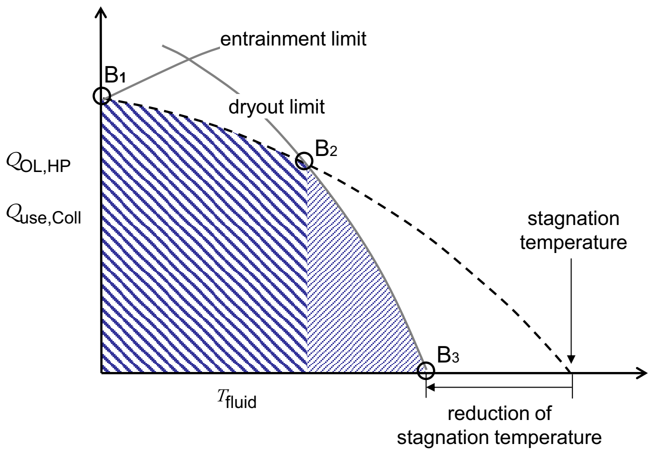

Figure 5: Schematic representation of the design criteria taking into account the required heat transfer rates and the heat transfer limits, depending on the temperature of the solar circuit fluid.

We have designed several flat plate collector prototypes with copper and aluminum heat pipes, using a commercially available frame and glazing (insulation thickness d = 50 mm, transmittance of the glass pane $\tau_{glass} \approx 0.9$). The heat pipes, filled with a defined amount of acetone, were manufactured at the ISFH and assembled on spectrally selective aluminum absorber plates (absorbance α_{abs} = 0.95, emissivity ε_{abs} = 0.05) by laser welding. The heat pipe condensers have been firmly bonded to copper manifolds. In the following, the collector with copper heat pipes is called P.1 and the collector with aluminum heat pipes is called P.1.1. Figure 6 shows partial views of the collector prototypes.

Figure 5: Backside of the aluminum absorber sheet with aluminum heat pipes connected by laser welding (left) and flat plate collector prototype P.1 (right).

The efficiency of the prototypes was measured in the ISFH sun simulator at different inclination angles and mass flow rates. The conversion factor η_0 ranged from 0.68 to 0.76. Figure 7 shows the measured collector efficiency curves for P.1 at an inclination angle of 45 °, and for collector P.1.1 at inclination angles of 20 ° and 45 °. In the range of the heat pipe dry out up to $\eta = 0$ a higher resolution of measuring points was used. For temperatures above 115 °C, the dry out limit of the heat pipes influences the collector efficiency. Starting from this temperature, the transferred heat rate of the heat pipes is limited. At a mean fluid temperature of about 130 °C, the efficiency is zero, which means that the temperature of the heat transfer medium in the solar circuit is limited to that value. This was measured during the collector efficiency test with an average wind speed of 3 m/s and an ambient temperature of about 25 °C.

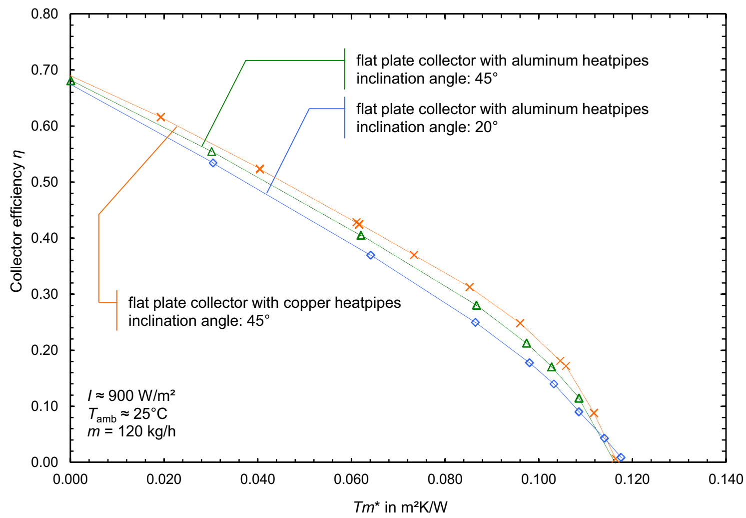

Figure 7: Measured efficiency curves of novel flat-plate collector prototypes with reduced performance at high temperatures due the use of deactivating heat pipes for different tube materials and inclination angles.

The influence of the deactivating heat pipes is clearly recognizable from the collector efficiency curves, but does not seem to be very large. This effect is much clearer, if the temperature distribution in the whole collector is considered. Figure 8 shows the temperature distribution along one heat pipe in the middle of the collector P.1 at several operating points (T_{fluid} = 25 °C, 100 °C and 130 °C). At a fluid temperature of 130 °C the collector efficiency is zero, the stagnation point of the collector is reached. The results were measured during the collector efficiency measurement at G ≈ 900 W/m² und T_{amb} ≈ 25 °C.

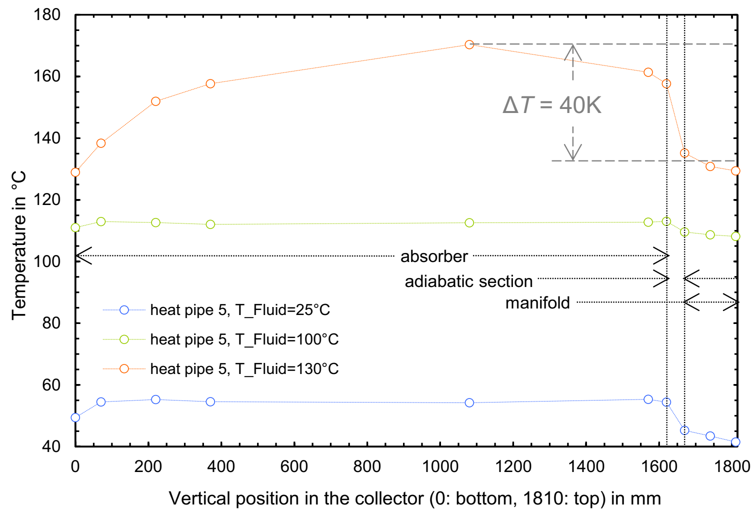

Figure 8: Measurement results of the temperature distribution along a heat pipe at the center of the collector P.1 for the operating point at 25 °C and 100 °C mean fluid temperature, and for the case of stagnation (T_{fluid} = 130 °C)

In a built system with real weather conditions more severe thermal loads in case of stagnation compared to the efficiency measurement can be expected. In addition to high radiation and high ambient temperatures very low wind speeds can occur and the solar circuit pump is powered-off. To reproduce this more realistic case of stagnation the collector pump and the artificial wind are turned off. For an additional measurement the fluid circuit is completely removed from the collector. The results are shown in table 1.

For the case without wind and connected collector circuit without fluid flow, maximum temperatures of 138 °C are measured at the fluid circuit for both collectors. The temperatures at 2/3 height of the absorber, however, reached values close to 180 °C. The maximum stagnation temperature of the fluid circuit is about 40 K below the maximum temperature at the absorber plate. At an elevated irradiance of 1000 W/m² and an ambient temperature of 30 °C a maximum temperature on the absorber plate of more than 200 °C is expected.

Table 1: Measured stagnation temperature at 2/3 height of the absorber plate and in the middle of the manifold at different test conditions for the collectors P.1 and P.1.1 for an irradiance of 900 W/m² and an ambient temperature of about 26 °C.

	P.1 Copper heat pipes		P.1.1 Aluminum heat pipes	
	$T_{abs,2/3}$ in °C	$T_{man,max}$ in °C	$T_{abs,2/3}$ in °C	$T_{man,max}$ in °C
Connected fluid circuit, with fluid flow and wind	171,3	131,6	164,4	128,6
Connected fluid circuit, no fluid flow, no wind	178,9	138,3	179,7	137,8
Fluid circuit not connected, no wind	188,4	142,0		

The temperature at the fluid circuit is not significantly increased due to the thermal decoupling by deactivating heat pipes, so that even a more significant reduction of the maximum temperature from the absorber plate to the fluid circuit can be expected. A limitation of the maximum temperature at the fluid circuit to even lower values may be possible by optimizing the heat pipes. Replacing copper with aluminum heat pipes can reduce the material cost without compromising the system safety. Since the solar circuit fluid is only in contact with the pipes of the manifold, which are made of copper, corrosion in the solar circuit can be avoided, contrary to other technology approaches.

5. Reduction of system costs due to limited stagnation loads

Generally, the production costs of the collectors represent only a small part of the overall costs of solar thermal installations. However, significant saving potential can be found in the field of systems engineering, because the system complexity (connection of the collector array, large expansion tanks, temperature-resistant components and optional cooling lines or drain back solutions) generate high costs.

Especially the vapor formation in case of stagnation has a significant influence on the expenses for the installing crafts, because they take a surcharge due to uncertainty in the operational safety (Hafner 2013). Other aspects are the ventilation and degasification as well as the hydraulic balance, which can be realized much more easily in a simplified hydraulic system, as it exists with heat pipes. Thus, an increased operating reliability due to stagnation safe collectors can also lead to lower extra charges on the material costs by the craftsmen.

With the developed collector technology, the stagnation temperatures in the fluid circuit can be limited to 100 °C up to 160 °C depending on the heat pipe design. Thus, they are well below today's evacuated tube collectors (up to 300 °C) and flat plate collectors (up to 210 °C). This results in significant benefits as described in the following:

- The degradation of the heat conducting paste between the heat pipe condenser and the manifold, which leads to an increased heat transfer resistance and hence to an efficiency loss can be reduced or avoided. If necessary, a replacement of individual vacuum tubes is easily possible even after a long period of operation, because the heat conducting paste is still flexible.
- Due to the lower temperature load in the solar circuit in case of stagnation, the solar circuit pipework can be performed simpler. For example, hard-soldering of pipe joints is not necessary and with optimized shutdown even a polymer tubing is possible.
- With a defined shutdown temperature and a slightly elevated operating pressure, it can be prevented that fluid evaporates in the solar circuit and spreads across the system. Otherwise, the propagation of steam could cause destruction of pumps, valves and other components of the system. With temperature limiting collectors, expansion tanks can be sized smaller and less expensive without an additional in-line vessel.
- Currently, expensive cooling systems or complex solar circuits are sometimes used in systems without shutdown. These protection systems include temperature controls, valves and more. These additional units can be avoided by using temperature limiting collectors.
- Usually, the water-glycol mixture in the solar circuit cracks at the high temperatures occurring in case of stagnation. As a result, the solar circuit fluid has to be changed frequently, which is preventable.
- The simpler hydraulic configuration of the solar circuit in the heat pipe collectors leads to simplification of the collector array pipework and a higher reliability. Parallel connections of collectors can be reduced and partial stagnation, which may occur for evacuated tube collectors with coaxial tubes, can be avoided (Glembin et al. 2010).
- By avoiding vapor formation and thus reducing system load during stagnation the error rate of solar installations is reduced, thus their reliability is increased.

We have investigated possible system simplifications to quantify the cost reduction potential for solar thermal installations due to the use of temperature limiting heat pipe collectors. For the assessment of the potential savings, also experts from industry and craft have been consulted. In the following, our approaches are briefly presented. Detailed information regarding the assumptions made and the cost calculation is presented in Jack and Rockendorf (2013) and Jack et al. (2014).

For our investigations, an installation with a collector area of 5 m² was assumed. A simplification of the solar station and additionally the use of a collector field piping made of plastics instead of the traditional copper piping has been considered. Overall, a reduction of specific investment costs related to the collector area of 100 €/m² is expected.

A further lowering of costs can be achieved by the reduction of the volume of the expansion vessel. The dimensioning of the expansion vessel according to Scheuren and Kirchner (2008) with the expected steam range during stagnation in combination with a cost evaluation results in a further cost reduction of 10 €/m². Due to the simpler system hydraulics, also cost savings in installation and commissioning can be achieved.

The lower effort for the installation of piping and for filling and venting of the system, further reduces the system costs by 48 €/m².

Furthermore, the maintenance costs of the systems compared to the present state can be reduced significantly. These are particularly the extension of the maintenance intervals and a significantly longer service life of the solar circuit fluid. A cost reduction of 55 €/m² was estimated for a lifetime of 20 years.

Considering additional aspects (simpler collector interconnection, no pump replacement) and a financing of the investment and the time-based maintenance, we expect a possible cost reduction of about 25%.

6. Conclusion

Basically the approach of deactivating collectors can transfer the complexity of the solar circuit to the collector. By using the dry out limitation of gravitational heat pipes with organic working fluids, temperatures in the collector can be significantly reduced in the case of stagnation, so vapor formation can be avoided. Novel flat plate collector prototypes have been designed, built and tested, which limit the stagnation temperature in the heat transfer medium of the solar circuit in the collector to 140 °C. Theoretical considerations on the dry-out limit of heat pipes show that an improvement to 120 °C is achievable. This would result in a maximum stagnation temperature at the collector connections of below 100 °C , which can lead to drastic system simplifications. Completely new plug-and-play solar circuits made of polymers will be possible.

By means of exemplary considerations we have shown that a system installation with deactivating collectors can be significantly cheaper. For small systems (one and two family dwelling units), we expect a cost reduction potential for the solar system of at least 25 %.

Thus, the use of deactivating collectors with heat pipes can lead to savings that go far beyond the potential savings of cheaper collectors. The systems are simpler, which relieves the installer and they are more reliable, which lowers the risk and guarantees the yield. Hence heat pipes in collectors represent a potential key technology for simplification and cost reduction of solar thermal systems.

7. Acknowledgement

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