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Butane heat pipes for stagnation temperature reduction of solar thermal collectors

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Abstract

Heat pipes in solar thermal collectors enable to reduce the temperature loads in the solar circuit during stagnation periods by exploiting their dry out limit. Typically water, pentane or acetone are used as heat transfer media in collector heat pipes. Butane is very suitable to reach a high temperature gradient of the dry out even if the maximum temperature in the fluid circuit should be designed to 120°C or below. The paper presents experimental results with butane heat pipes that operate up to a maximum temperature of 120°C with a high temperature gradient in the dry-out region. This ensures that the collector performance in the operating range (typically up to 100°C) is not affected negatively by the dry-out. Different approaches to increase the thermal conductance of butane heat pipes by enhancing the inner surface of the condenser or of both, the condenser and the evaporator are experimentally assessed and discussed. Measurement results report an increase of the heat pipes' thermal conductance from 3 W/K (standard geometry) to 23 W/K.

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Keywords: heat pipe, stagnation temperature, cost reduction, butane, flat plate collector, evacuated tube collector

1. Introduction

Heat pipes in solar thermal collectors are state-of-the-art devices for solar heat transfer from the absorber plate to the heat transfer medium inside the collector. This technology is established for evacuated tube collectors, for flat

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plate collectors it has up to now only been demonstrated in research projects (e.g. [1]).

As the heat pipe is an additional component in the heat transfer path between the absorber plate and the collector fluid in the manifold (see Fig. 1), a high thermal conductance of the heat pipe is essential to achieve a high collector efficiency. Further the heat pipe decouples the absorber plate from the fluid circuit. If the heat transfer by two-phase flow inside the heat pipe is stopped, beginning from a certain temperature, the maximum temperature in the solar fluid can be limited to reduce thermal loads. The deactivation of the heat transfer process can be achieved by employing the dry-out limit of heat pipes. With this approach vapour formation in the solar circuit can be completely avoided which is essential to reduce costs of solar thermal systems by simplified and more reliable solar circuits.

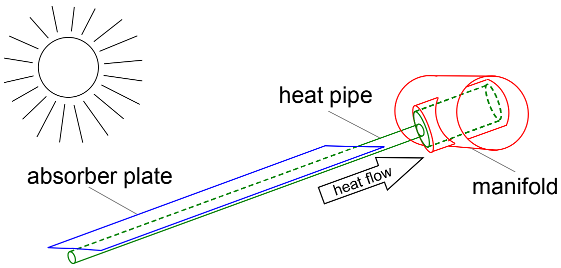


Fig. 1. Schematical drawing of a solar thermal collector configuration with a heat pipe as an additional component between the absorber plate and the manifold

2. Butane as heat transfer medium in heat pipes

The thermodynamic properties of the heat transfer medium in the heat pipe strongly influence the thermal conductance and the dry-out temperature. State-of-the-art media used in collector heat pipes are water or organic media like ketones (e.g. acetone) or alkanes (e.g. hexane) [2].

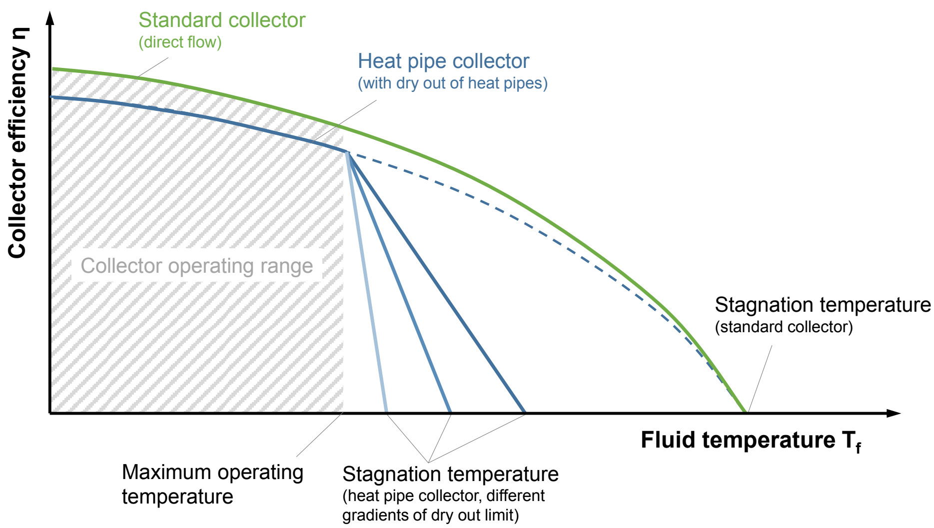


Fig. 2. Stagnation temperature (defined as the maximum fluid temperature without internal heat removal) according to the collector efficiency curve for a standard collector (direct flow) and a heat pipe collector with different gradients of the deactivation due to the dry out limit (schematic illustration).

Resulting from an investigation with possible heat transfer media using validated theoretical models ([2, 3]), butane has been identified as very suitable to reach a very sharp deactivation of the heat transfer. This means, that the heat transfer is switched off from a high heat flow rate in the operating range to nearly zero within a very small temperature range. A high gradient of the heat pipes' heat flow rate in the temperature range of the dry-out limit is essential to reach both a high collector performance in the operating range and low maximum temperature loads in the solar circuit in case of stagnation. It allows to limit the maximum temperature in the solar circuit close to the maximum collector operating temperature without affecting the collector performance in the operating range, as Figure 2 illustrates. Thus the collector performance for system operation is not influenced negatively by the deactivation.

However, the heat transfer capability with butane in the operating range for a typical heat pipe geometry is lower compared to other organic media, like e.g. acetone. This is mainly caused by butanes' comparatively low values for thermal conductance and enthalpy of vaporization. Thus optimization of butane heat-pipes is essential to reach a high thermal conductance. One approach is to enlarge the active surfaces for condensation and/or evaporation, which are described in the following chapter.

3. Experimental results

To carry out experimental investigations with collector heat pipes employing butane, we developed a laboratory device, which allows us to fill the heat pipes and to seal them properly. We measured the thermal performance of first butane heat pipes with typical dimensions (d_{pipe} = 8 mm, l_{evap} = 1.73 m; l_{cond} = 0.08 m) using an existing test bench. As theoretically expected, the thermal conductance at a condenser temperature of 80°C of a butane heat pipe ($U_{butane} \approx$ 3W/K) is lower than for comparable heat pipes with acetone ($U_{acetone} \approx$ 5 W/K) as Figure 2 illustrates. Our development of heat-pipes focuses on both, the integration into evacuated tube collectors as well as into flat-plate collectors. Particularly for flat-plate collectors, a good thermal coupling of the condenser to the fluid circuit in the manifold essential to reach a suitably high collector efficiency. Thus for our first flat-plate prototype collectors we have chosen a manifold design with an enhanced condenser length, to increase the heat exchanging surface in the manifold. Results with these prototypes are published in [1].

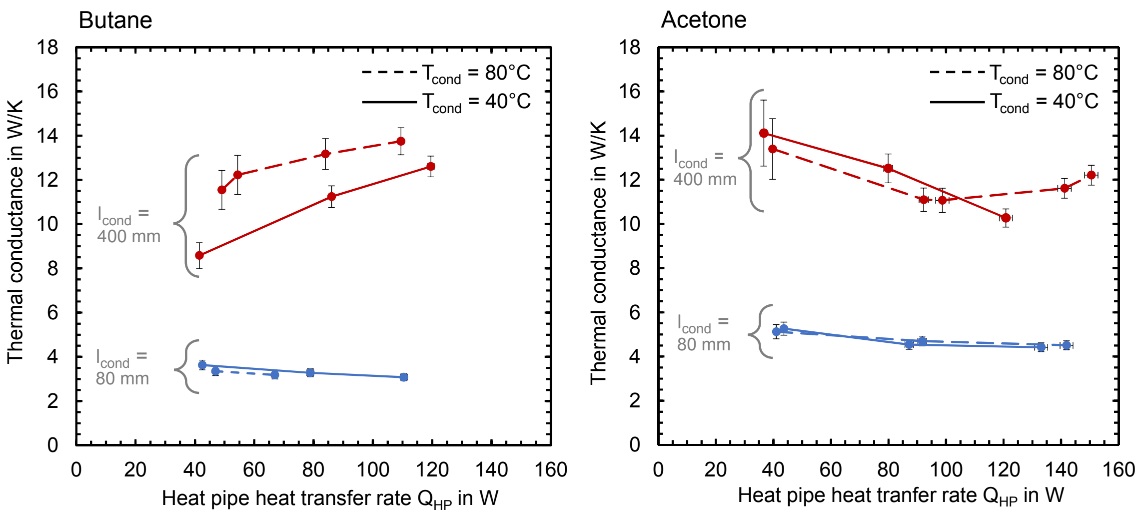


Fig. 3. Measured thermal conductance for butane-filled heat pipes (left diagram) and acetone filled heat pipes (right diagram) with different condenser lengths l_{cond} = 80 mm and 400 mm for two different condenser temperatures (T_{cond} = 40°C and 80°C)

The typical geometry for collector heat pipes, which is characterized by a very small condenser length (e.g. l_{cond} = 80 mm), compared to the evaporator length (e.g. l_{evap} = 1730 mm) leads to very high heat fluxes in the condenser zone. Thus the overall heat transfer of the heat pipe is mainly limited by the heat transfer in the condensation zone. With enlarging the surface of the condenser, the influence of the thermal conductance in the evaporator on the overall heat transfer ability is increased. The comparatively low surface tension of butane leads to high thermal conductances in the evaporation zone. By enlarging the condenser surface five-fold from l_{cond} = 80 mm to l_{cond} = 400 mm the overall thermal conductance of the heat pipe at T_{cond} = 80°C and Q_{HP} = 60W is increased nearly proportional to the condenser surface to 13 W/K (factor 4.3), as Figure 3 illustrates.

Because of butane's comparatively high heat transfer ability in the evaporator zone, the heat pipes' overall thermal conductance is dominated by the condensation heat transfer, even with a significantly increased condenser surface.

With acetone the thermal conductance by evaporation is lower. Thus the heat pipes' overall thermal conductance with enlarging the condenser surface is more pronounced by the thermal conductance of evaporation. At the same conditions (T_{cond} = 80°C and Q_{HP} = 60W) enlarging the condenser surface five-fold the thermal conductance is increased only to 12 W/K (factor 2.4).

One essential benefit of butane in solar thermal collectors is the ability to reach a dry-out with a high temperature gradient. As Figure 4 shows, the measured heat pipe power in the range of the dry-out limit for acetone as well as for butane shows a good correlation with the theoretically determined curves. If the heat pipe is filled with 5.5 g of butane, a maximum condenser temperature of 110°C is achieved and the operating range of the collector is not affected negatively. In contrast to that, a reduced mass of 1.5 g for acetone also leads to a reduced maximum condenser temperature, but in the typical operating range of solar collectors, the dry-out limit reduces the collector performance significantly.

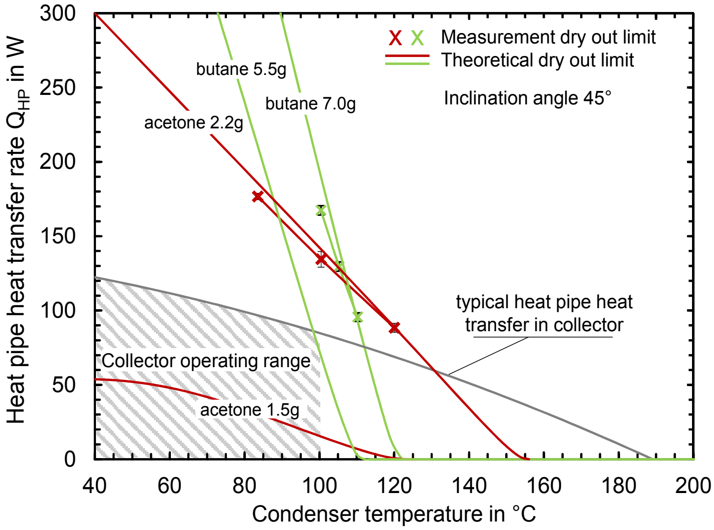
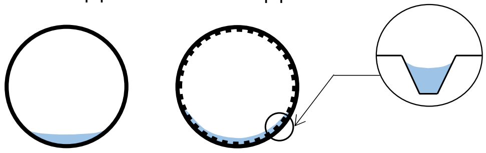


Fig. 4. Measured and calculated heat pipe heat transfer rate in the range of the dry out limit for butane (mass of 7.0 g and 5.5 g) and for acetone (m = 2.2 g and m = 1.5 g) compared to the typical heat transfer of one heat pipe in a solar collector.

To further raise the thermal performance of butane heat pipes, we experimentally investigated enhancing the inner surface area for evaporation as well as for condensation using helical grooves on the inner surface of the heat pipe. The trapezoidal grooves, as shown in Figure 5, are rotated around the pipes' longitudinal axis with a helix angle of 18°. Compared to the smooth pipe, the inner surface area of the grooved pipe is enlarged by a factor of 1.6.

For the experimental characterization for both the grooved and the smooth pipe the length of evaporator (l_{evap} = 1670 mm) and condenser (l_{evap} = 260 mm) are identical.



	Smooth pipe	Grooved pipe
Inner surface area (1m pipe length)	0.027 m²/m	0.042 m²/m
Outer diameter	9.5 mm	9.5 mm
Inner diameter	8.6 mm	8.6 mm

Fig. 5. Geometric shape and dimension of the grooved pipe compared to the smooth pipe as a reference, the condensate flow in the evaporator zone is schematically illustrated.

The adiabatic zone between the condenser and the evaporator is dimensioned larger than usual for collector heat pipes exhibiting a length of 0.36 m. This allows the application of a total of 18 temperature sensors in this area in order to determine the mean temperature of the transport zone. With regard to this temperature, it becomes possible to determine the individual conductance for evaporation and condensation in addition to the thermal conductivity of the entire heat pipe.

The effect of the internal grooves on the overall thermal conductance of the heat pipe is illustrated in Figure 6. With condenser temperatures of 40°C and 80°C the thermal conductance is approximately doubled compared to the smooth surface. In contrast to the smooth pipe, the thermal conductance of the grooved pipe decreases with increasing heat transfer rate. The main reason seems to be the overflow of the grooves in the condenser zone due to the increased condensation film thickness. This reduces the effectiveness of the enlarged condenser area by grooving. This is apparent in the separate consideration of the conductance by condensation and by evaporation, as Figure 7 shows.

The thermal conductance by evaporation and by condensation for the smooth pipe are both in the same range, e.g. at Q_{HP} = 60W between 15 W/K and 25 W/K. For the grooved pipes, the conductance for evaporation is significantly higher than the one for evaporation. This demonstrates that the positive effect of the grooves on the heat transfer in the heat pipe affects the evaporation more than the condensation.

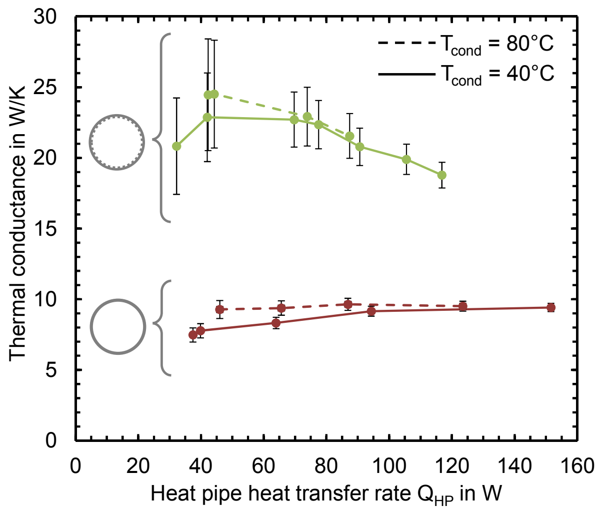


Fig. 6. Measured thermal conductance of butane filled heat pipes at condenser temperatures of T_{cond} = 40°C and 80°C with smooth inner surface compared to a pipe with grooved inner surface, both with the same length of condenser and evaporator zone (l_{cond}= 260 mm, l_{evap}= 1730 mm).

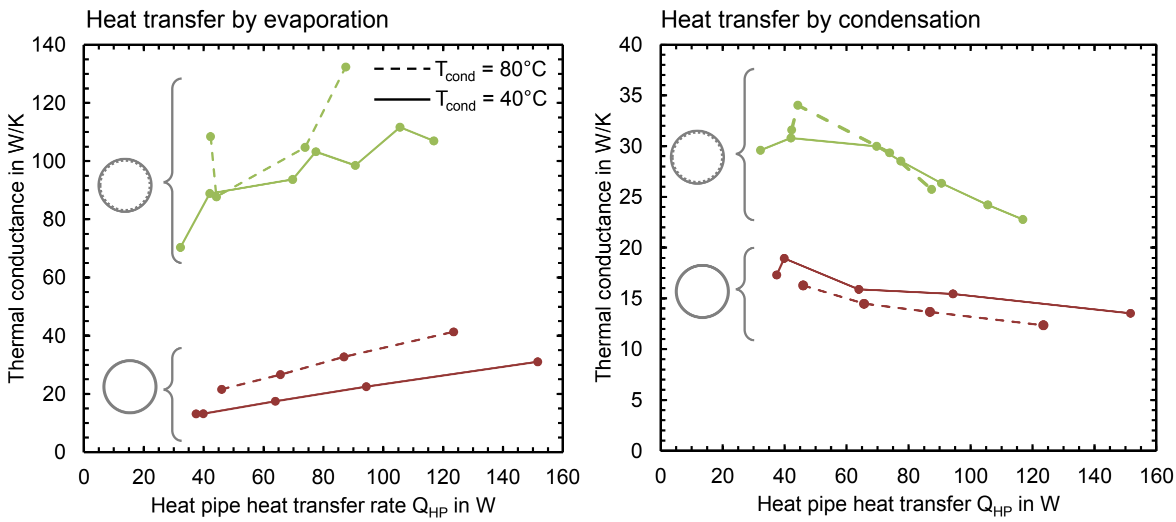


Fig. 7. Measured thermal conductances at the evaporator (left diagram) and the condensator (right diagram) of butane filled heat pipes at condenser temperatures of T_{cond} = 40°C and 80°C with smooth inner surface compared to a pipe with grooved inner surface, both with the same length of condenser and evaporator zone (l_{cond}= 260 mm, l_{evap}= 1730 mm).

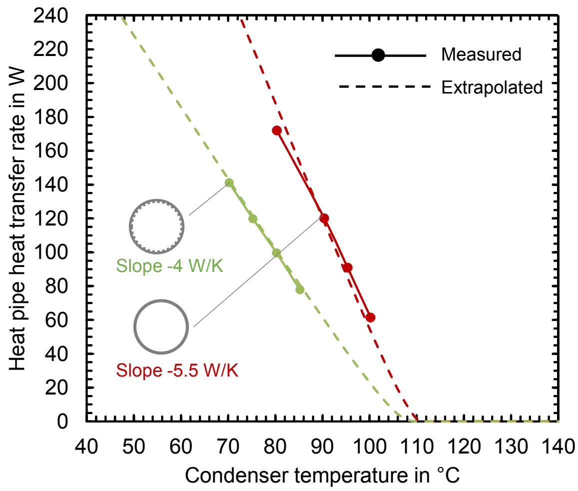


Fig. 8. Measured heat pipe heat transfer rate for varying condenser temperature in the range of the dry-out limit for with smooth inner surface compared to a pipe with grooved inner surface, both with the same length of condenser and evaporator zone (l_{cond}= 260 mm, l_{evap}= 1730 mm).

Grooving the inner surface also affects the dry out behavior of the heat pipe. As Figure 8 illustrates, the slope of the heat transfer rate in the range of the dry-out decreases. With the smooth pipe a slope of -5.5 W/K is achieved whereas with the grooved pipe it is decreased to -4 W/K. This behavior of the internally grooved pipe can be attributed to the increased surface area and improved wetting of the evaporator. With increasing the condenser temperature the two phase equilibrium in the heat pipe is shifted towards the vapour phase. Thus the proportion of vapour increases whereas the one of condensate is reduced. By reducing the amount of condensate due to a raised temperature, the reduction of the wetted evaporator surface begins at lower temperatures for the grooved pipe as for the smooth pipe. Thus, the effect of the dry-out limit starts to reduce the heat transfer rate at lower temperatures.

This negative effect for the desired application in the collector is currently further investigated. An experimental study with a modified helix angle is planned to gain more knowledge about this effect.

4. Conclusion

As a heat transfer medium in collector heat pipes, butane has been identified as very suitable to reach a high temperature gradient of the dry out even if the maximum temperature in the fluid circuit should be designed to 120°C or below. Experimental investigations show, that the thermal conductance of butane heat pipes with collector-typical dimensions (l_{cond} = 80 mm) is significantly lower, compared to acetone heat pipes. By increasing the condenser area five-fold the butane hat pipe exhibits a thermal conductance, which is in the same range to that of an acetone heat pipe with the same dimensions. To further increase the thermal performance, butane heat pipes with helical grooves on the inner surface were manufactured and characterized. With this approach the surface area and the wetting of the surface by the heat transfer medium in the evaporator as well as in the condenser zone is increased. Experimental characterizations showed, that the thermal conductance of a typical collector heat pipe is more than doubled using grooved pipes. For a condenser length l_{cond} = 260 mm and an evaporator length l_{evap} = 1670 mm the thermal conductance is increased from 10 W/K to 23 W/K (T_{cond} = 80°C, Q_{HP} = 60W).

Heat pipes with butane as a heat transfer medium can limit the maximum temperature in the solar circuit of solar thermal collectors to 120°C or below, while enabling a high collector performance in the collector's operating range. Thus evaporation of the solar fluid can be completely avoided using a typical operating pressure.

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