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Effects of measurement conditions on operating limits of solar horizontal heat pipes

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Abstract

In this work operating limit measurements are presented for one self-fabricated and one commercial solar heat pipe at horizontal and small inclination angles. While for the self-fabricated test sample heat transfer is limited by entrainment, dry-out limit is observed for the commercial solar heat pipe. Operating limit measurements of the commercial solar heat pipe show good reproducibility, whereas the detected operating limit of the self-fabricated heat pipe varies drastically. When tested at slight inclination, high temperature oscillations indicating geyser boiling effects are observed for the commercial test sample. Finally, operating limit definitions given by the literature are discussed regarding their applicability for solar thermal applications.

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Keywords: heat pipe; two-phase thermosyphon; solar collector; horizontal operation; operating limits; heat transfer limits

1. Introduction

1.1. Motivation

High flexibility in architectural design is the key for a broad application and acceptance of solar thermal façade integration. Solar collectors which use heat pipes or closed two-phase thermosyphons to transport the energy from the absorber to the manifold are an interesting option for this purpose. The separation of the hydraulic circuit of the

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Nomenclature

Q	power (W)	*ev*	evaporator
T	temperature (°C)	*elec*	electric
		pool	pool boiling region
Subscripts		*film*	film boiling region
ad	adiabatic		

absorber and the manifold constitutes the basis for the development of highly modular and flexible collector concepts. Especially the so called "dry connection" of the heat pipe or two-phase thermosyphon to the manifold allows for modular collector concepts leading to high architectural flexibility in design and thermal output. Moreover, it is expected that with those modular collector concepts also production, installation and maintenance costs can be reduced. Two examples of architecturally highly integrated heat pipe solar façade collector concepts being developed at Fraunhofer ISE are presented in Fig. 1.

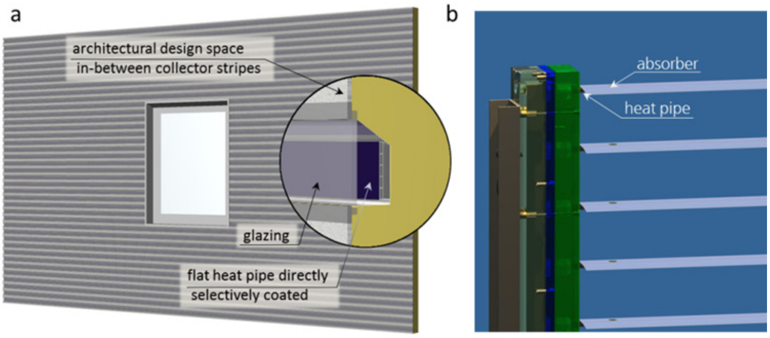

Fig. 1. Modular solar façade collector concepts using heat pipes: (a) stripe collector; (b) venetian blind.

State of the art solar collectors operate with closed two-phase thermosyphons. While heat pipes use capillary forces to recirculate the condensate to the evaporator, closed two-phase thermosyphons resort to gravitational forces [1,2][1]. Therefore, state-of-the-art standard collectors only operate successfully at a specific minimum inclination. As a consequence, the advantage of "high modularity" is opposed to the disadvantage of "orientation restriction" of the two-phase thermosyphon. However, a reliable operation at various – also horizontal – inclination angles is significant to achieve high design freedom and thus acceptance of solar façade integration by architects.

Before including wick structures, the simplest option to enlarge the operating envelope of closed two-phase thermosyphons towards horizontal is the "overfilling" of the thermosyphon using higher fill rates [3]. While "overfilling" increases the dry-out limit, the entrainment and flooding limits are decreased. Therefore, a profound investigation of the operating limits of horizontal and slightly inclined two-phase thermosyphons is the first step in analyzing and developing flexible collector concepts for successful solar façade integration.

[1] As in solar industry the term "heat pipe" is also often used for two-phase thermosyphons, this paper refers to the term "heat pipe" as a hypernym for both heat transfer devices whenever no clear declaration is needed.

1.2. Literature review

Scientific publications on horizontal or slightly inclined two-phase thermosyphons are limited. A number of authors presented work on two-phase thermosyphons operating under horizontal orientation (sometimes having inclined condenser parts) [4–9], most of them aiming for applications in permafrost region foundation design. However, operating limits were not put into focus.

In regard to solar thermal applications Xinian et al. proposed different thermosyphon designs for horizontal balcony applications of vacuum tube collectors [10]. Wang et al. were the first to present an experimental study on solar horizontal heat pipes. They investigated the effect of fill rate and small changes in inclination angle on the heat transferred [11]. According to the results the optimum fill rate leading to highest heat transfer was said to be in between 19.1 % and 22.4 % (ratio of fill height to inner diameter). Water or steam hammer sounds were noticed at the highest fill rate of 32.3 %. At an inclination angle of +0.5° (condenser above evaporator) a significantly higher heat transfer capacity was measured. However, consistent water hammering occurred. At an inclination angle of -0.5° (evaporator above condenser) the heat transfer capacity was seriously reduced. A high sensitivity of the solar horizontal heat pipe to inclination angle was concluded. However, no information on the measurement accuracy of inclination angle or filling amount was given. As measured heat transfer capacities show high fluctuations (e.g. 88.59 Watt at 22 ml filling amount and 48.07 Watt at 21.8 ml filling amount), clear dependencies are debatable.

The – to the knowledge of the author – only experimental analysis on heat transfer limits of horizontal closed two-phase thermosyphons was done by Bezrodny & Podgoretskii [3]. Heat transfer limit experiments were carried out on a stainless steel two-phase thermosyphon. As working fluids water, propanol, acetone and freon-11 were used. Heat was supplied to the evaporator by steam heating. During heat transfer limit experiments the electrical load in the steam generator was varied in steps while the pressure in the thermosyphon was held constant by varying the water flow rate of the condenser jacket. Glass inserts in the middle and at the end faces of the test thermosyphon allowed to visualize the flow. By varying the fill rate, an optimum filling ratio leading to maximum limiting heat flux was identified. Experiments at different inclination angles revealed an essential dependency of the limiting heat flux on the filling ratio in the region of small inclination angles of 0-2°. Equations were given to calculate the limiting heat transfer capacity of horizontal and inclined thermosyphons being valid under conditions of steam and convective heating.

Nguyen-Chi & Groll presented investigations on the entrainment or flooding limit of a copper-water thermosyphons (which had fine circumferential grooves on its inner surface) including small inclination angles of 1, 2 and 5° towards horizontal [12]. While increasing the heat load in steps, the surface temperature profile of the thermosyphon was recorded. At a certain power temperature fluctuations appeared which were accompanied by a periodic noise. With further increase of heat supply temperatures suddenly started to increase drastically. The corresponding heat load was defined as the performance limit of flooding. In addition to the effect of operating temperature the impact of fill rate on the maximum heat flux was analyzed. In opposition to Bezrodny & Podgoretskii [3] the results of Nguyen-Chi & Groll showed only a weak influence of fill rate on the maximum heat flux being even less pronounced for small inclination angles than for greater ones.

1.3. Scope of work

As literature review reveals, little research work has been done so far on heat transfer limits of horizontal or slightly inclined closed two-phase thermosyphons. Moreover, in existing work in some cases no clear dependencies could be found or even opposed results were obtained. Therefore, before analyzing the effect of heat pipe and operating parameters as fill rate, diameter, working fluid or working pressure, the effect of measurement and test sample conditions on measured operating limit values has to be investigated and reproducibility of results has to be studied. The present paper is the first step in this important work. Therefore, multiple runs of heat transfer measurements shall be carried out for one self-fabricated and one commercial solar heat pipe at horizontal and small inclination angles. Especially the effect of post-oxidation of heat pipe container on the reproducibility of heat transfer limit measurements shall be analyzed. Finally, operating limit definitions given by the literature shall be discussed regarding their applicability for solar thermal applications.

2. Short theory of operating limits

Heat pipes transfer heat by a circuit of evaporation and condensation. While during normal operation heat pipes are characterized by thermal resistances, operating limits describe boundaries where normal evaporation and condensation processes are disturbed by physical effects. Depending on the physical effect when reaching an operating limit the heat transfer either cannot be increased in the same way as during normal operation, cannot be increased any more at all or even can suddenly decline [1]. While the physical effects of the different operating (or heat transfer) limits have been widely investigated, the definition of limits is – as is the kernel of definitions – up to the author and therefore differs a lot. This paper refers to the definitions of Nguyen-Chi and Groll [12].

According to Nguyen-Chi and Groll, the most important performance limits of closed two-phase thermosyphons are the dry-out limit, the burn-out or boiling limit and the entrainment or flooding limit. Dry-out occurs at the end of the evaporator or above the liquid pool level when the quantity of working fluid required for the circulation of vapor and condensate for a given heat input is too small. While dry-out limit dominates for relatively small radial evaporator heat fluxes, burn-out or boiling limit occurs at high radial evaporator heat fluxes. When nucleate boiling becomes more intense with increasing power, vapor bubbles aggregate to form a vapor film insulating the evaporator wall and thus disturbing normal thermosyphon operation. Entrainment or flooding limit prevails for high axial, but small radial evaporator heat fluxes. With increasing power the relative velocity between vapor and condensate flow increases. Thereby, shear stresses at the vapor/liquid interface increase and surface waves are induced. At a certain power shear stresses are so high that vapor entrains droplets out of the condensate flow. Entrainment limit is reached. With further increase of power, shear stresses can fully stop the returning condensate flow back to the evaporator. Nguyen-Chi and Groll define this point as flooding limit [12].

Solar heat pipes are typically characterized by small radial evaporator heat fluxes. Therefore, dry-out and entrainment or flooding limit are the dominating operating limits. According to Bezrodny & Podgoretskii [3] thermosyphon operation will be limited by dry-out if the filling ratio is below its optimum value, while entrainment or flooding prevails if the filling ratio exceeds its optimum value.

3. Experimental procedure

3.1. Test samples

Table 1 gives characteristic parameters of the self-fabricated (ThSy_1) and the commercial test sample (Com_1). The commercial test sample is part of a solar collector which by the manufacturer is proposed for inclinations angles between 0° and 90°. Within the whole work the fill rate is defined as the ratio of the liquid working fluid volume filled into the thermosyphon to the total container volume of the thermosyphon. The estimation of the fill rate of the commercial thermosyphon is based on longitudinal temperature profile measurements at an angle of 45°. The break in the characteristic temperature profile of film and pool boiling regions (e.g. see [13]) gives evidence of the position of fluid level and therefore of the fill rate.

Fig. 2 a shows the setup of the heat pipe filling rig. To reduce the content of noncondensable gases, the heat pipe container is degassed before filling for at least twelve hours by a vacuum pump at temperatures around 120 °C. For the same reason working fluid (DI water) is degassed by freeze degassing before raining it out into the container (s. Fig. 2 b). Then the container is closed by a needle valve and the fill rate is determined by weight measurement.

Table 1. Characteristic parameters of two-phase thermosyphon test samples.

Name of test sample		ThSy_1	Com_1
Container material		copper	copper
Working fluid		DI water	unknown
Total length	m	1.0	2.1
Outer diameter	mm	12	10/22*
Inner diameter	mm	10	unknown
Evaporator zone	mm	750	1800
Condenser zone	mm	110	90
Fill rate	%	49	16-25 (estimation)
Container pretreatment		defatting	unknown

* The first number indicates the diameter of the evaporator and adiabatic zone, the second of the condenser zone.

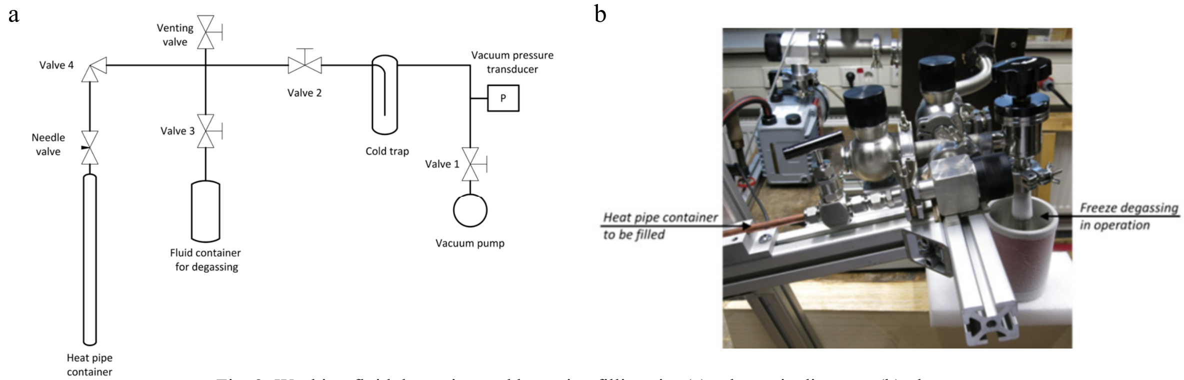

Fig. 2. Working fluid degassing and heat pipe filling rig: (a) schematic diagram; (b) photo.

3.2. Experimental setup and testing procedure

The experimental setup is shown in Fig. 3. To improve the accuracy in orientation, the thermosyphon is directly situated on pillars made out of PTFE having a low heat transfer coefficient and a low thermal expansion coefficient. By this, an inclination accuracy of 90.2° and 90.4° can be guaranteed for the self-fabricated and (longer) commercial test sample, respectively. While horizontal position is defined as 0°, positive angles characterize orientation with condenser above evaporator. As the kind of thermal boundary condition (temperature or power supply) is assumed to have a strong impact on evaporation and therefore heat pipe performance [3,14], heat is supplied to the evaporator by an electric heating wire simulating the power supply by the sun. To ensure homogenous heating, the heating wire is evenly coiled around the evaporator and fixed to the surface by wire. The supplied electric load is calculated by the product of the set voltage and the resulting current. The condenser is cooled by a cooling water jacket. The cooling water volume flow is regulated by an electric valve and measured by a magnetic inductive flow meter (MID). Inlet and outlet temperature of the cooling water as well as the water temperature next to the MID (for calculating the mass flow) are measured by Pt100 temperature sensors. The length of evaporator and condenser zone of the test samples can be found in Table 1. The temperature profile of the evaporator and adiabatic zone is measured by Pt100 chip sensors. To reduce the impact of the heating wire on temperature measurements, the wire is not directly placed above the temperature sensors which moreover are shielded by Kapton® tape and silicone caps. To ensure a good contact between sensor and thermosyphon surface, thermal grease is used and temperature sensors are pressed to the surface by strong fabric tape. Temperature sensors are evenly positioned along the top axis of evaporator and adiabatic zone, at some points also having sensors on the bottom of the tube. The error in surface temperature values is estimated to be within 90.25 °C. To reduce heat losses, evaporator and adiabatic zone are insulated by Pyrogel® mats and the whole setup is surrounded by blocks of mineral wool.

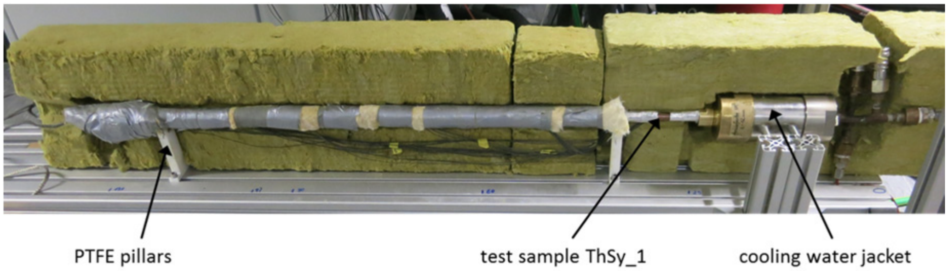

Fig. 3. Experimental setup for operating limit tests.

During operating limit tests the mass flow rate is held constant at 25 l/h (91 l/h) and the inlet temperature of the cooling water is set at 20°C (91 °C). The transferred heat is calculated by balancing cooling water inlet and outlet temperature.

To investigate the behavior of the thermosyphon with increasing load, the electric heat supply is varied in steps and the temperature profiles of evaporator and adiabatic zone are recorded. Referring to [3,15], the operating limit is said to be reached when the linear behavior of the temperature difference between evaporator zone and adiabatic zone as a function of the heat load applied is broken.

4. Results and discussion

4.1. Measurements of self-fabricated test sample

Table 2 gives a summary of the test conditions for every operating limit test run of the self-fabricated test sample ThSy_1. Different load and time intervals are chosen to analyze the influence of step height and step time during operating limit tests. In Fig. 4 temperature curves of evaporator and adiabatic zone are presented exemplarily for run A4 and A5. At a certain heat supply temperature oscillations occur. Temperature oscillations are the highest in the adiabatic zone where vapor velocity and thus interaction between vapor and liquid phase is the strongest. The linear dependence of the temperature difference betwen evaporator and adiabatic zone over electric load shows a clear break with the beginning of oscillations (s. Fig. 5) indicating a drastic change in thermosyphon operation. While all runs show good reproducibility during “normal” thermosyphon operation (linear relationship), the point of break differs drastically. In Table 2 the operating limit is given as range between the last power step of linear operation and the first power step breaking linearity. The existence of temperature oscillations indicates that the detected heat transfer limit is the entrainment limit.

Table 2. Characteristic parameters of operating limit test runs for test sample ThSy_1 and detected operating limit.

Run	Inclination angle [°]	Step height [W]	Step time [h]	Testing time after fabrication	Operating limit [W]
A1	0	≤ 10	≤ 0.5	< 3 weeks	95 - 103
A2	0	≤ 10	≤ 0.5	< 3 weeks	85 - 90
A3	0	10	≤ 0.5	< 3 weeks	70 - 80
A4	0	≤ 20	≥ 1	< 3 weeks	110 - 118
A5	0	≤ 20	≥ 1	≤ 3 weeks	20 - 40
A6	0	≤ 20	≥ 1	≤ 3 weeks	20 - 40
B1	0	20	≥ 1	≈ 2 months	60 - 80
B2	0	20	≥ 1	≈ 2 months	< 20
B3	0	20	≥ 1	≈ 2 months	< 20
B4	0	5	≤ 0.5	≈ 2 months	10 -15

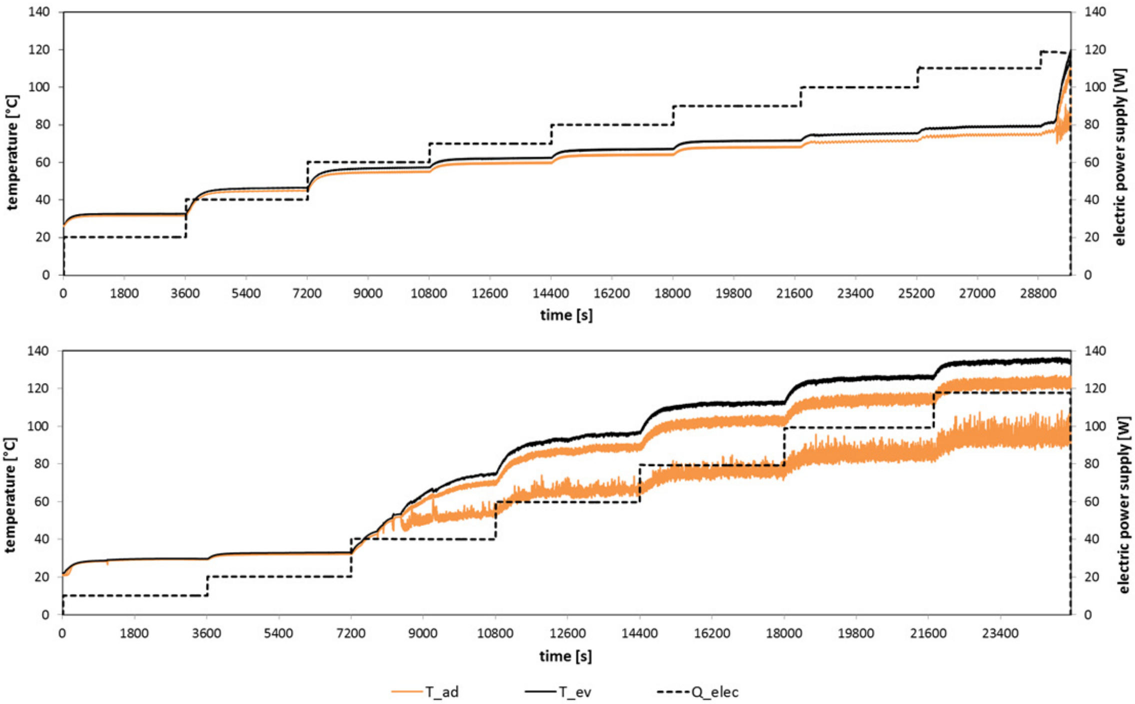

Fig. 4. Temperature curves of several sensors along the axis of the adiabatic zone (T_ad) and evaporator zone (T_ev) during operating limit tests (stepwise increase of heat supply Q_elec) for test sample ThSy_1 at horizontal orientation.

As the literature states [1,2], chemical reactions can occur after heat pipe fabrication e.g. leading to a change in wetting behavior or the generation of noncondensable gases. Thereby thermosyphon operation can be influenced during the first runs. To exclude post-oxidizing as reason for the drastic variation in the operating limit, sample ThSy_1 is tested again after two months when any post-oxidation is supposed to be concluded (s. runs B1- B4 in and Fig. 5). As can be seen from Table 2, even after two month operating limit measurements are still not reproducible. Therefore, post-oxidation is assumed not to be the reason for the drastic variation in the operating limit measurements. Test run B1 again shows similar behavior during “normal” operation (linear relationship) compared to run A1-A6 (s. Fig. 5). B2 and B3 already show temperature oscillations within the first step of 20 Watt. With decreasing step height during run B4 down to 5 Watt temperature oscillations already occur at a power of 15 Watt. In general, no clear influence of step height and time on the heat transfer limit can be detected. Further investigations have to reveal if the poor reproducibility of entrainment limit arises from instable test sample or measurement conditions or the instability being the essence of entrainment itself.

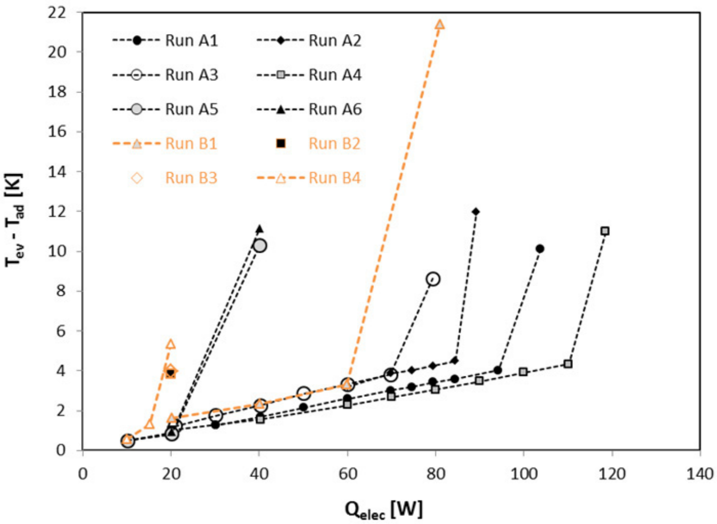

Fig. 5. Break in linearity of the temperature difference between adiabatic zone and evaporator and the electric power supplied indicating heat transfer limit.

4.2. Measurements of commercial test sample

Next to the self-fabricated test sample one commercial solar heat pipe is tested which has a notable lower filling ratio than the former one (for characteristic parameters s. Table 1). At an electric power supply of 40 W temperatures at the end of the evaporator start to increase drastically indicating that local dry-out occurs. At an inclination angle of +1° unstable dry-out phenomena occur between 40 and 60 W merging into a permanent dry-out of evaporator end at 80 Watt. Re-runs show reproducible results.

To prevent dry-out, the inclination angle is further increased to +4°. Instead of dry-out high temperature oscillations occur at a power of 40 W (s. Fig. 6). With increasing load the frequency of oscillations also increases. The appearing temperature curve resembles those being noticed for geyser boiling effects [16,17]. Under low pressure conditions vapor bubbles may grow to a very large size. When explosively being released they push the overlying liquid column towards the condenser. Therefore, evaporator surface temperatures of sensors being situated in the liquid pool suddenly decrease whereas those in the liquid film suddenly increase. During reference measurements at an inclination angle of 45° for Com_1 geyser boiling effects do not occur below 80 W whereas the self-fabricated test sample ThSy_1 already shows first geyser boiling oscillations at 20 W. Again, re-runs show reproducible results.

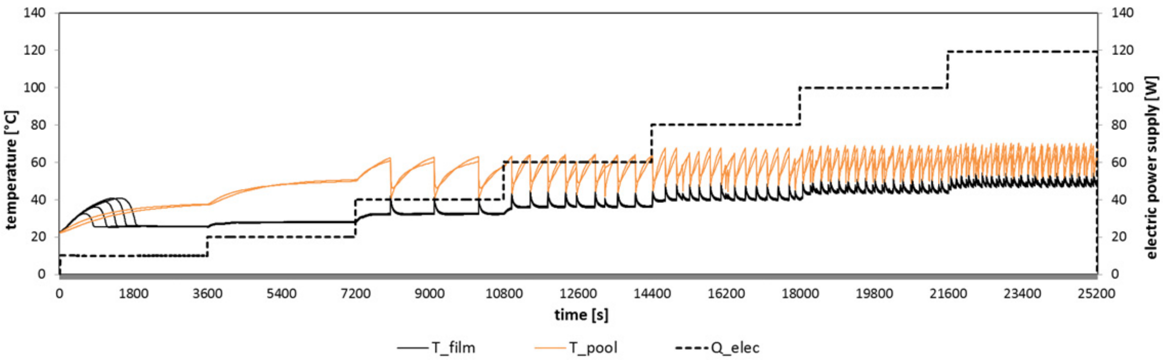

Fig. 6. Temperature oscillations at pool (T_pool) and film (T_film) boiling parts of evaporator (several sensors along the axis) at different heat supply (Q_elec) for test sample Com_1 at inclination angle of 4° towards horizontal.

4.3. Definition of operating limit

In this work the limiting heat flux was defined by the break in linearity of the temperature difference between evaporator and adiabatic zone and heat load supplied. However, increasing the electric load above the detected limit revealed that the transferred heat (estimated by balancing inlet and outlet cooling temperature) still could be increased up to ca. 130 Watt (run B1-B3). Thus a total breakdown of thermosyphon operation and thus flooding limit was not reached yet. Further increase of heat supply and therefore transferred heat was simply limited by the electric heating wire and temperature restrictions of temperature sensors used. However, with beginning entrainment the thermal resistance of the thermosyphon and therefore evaporator temperature increases thus increasing thermal losses and decreasing collector efficiency. To decide whether entrainment can be accepted during horizontal thermosyphon operation, a holistic analysis of solar gain and architectural benefit of horizontal collector orientation is required.

Even if geyser boiling is usually not named as physical operating limit in the literature, special attention should be paid on it. Being accompanied by high pressure jumps and “strange sounds” [17] geyser boiling might decrease lifetime and hinder acceptance of solar façade collectors.

In general, whether a certain operating limit value (or – since being dependent on temperature – rather “operating limit curve”) is sufficient for proper solar collector operation strongly depends on the heat pipe collector concept chosen. For instance, with a heat pipe array concept (several independent heat pipes in one extruded block being directly selectively coated), for test sample ThSy_1 already an operating limit of 10 Watt would be high enough not to hinder proper solar façade collector operation throughout the whole year.

5. Conclusion and future work

In this work operating limit measurements were carried out for horizontal and slightly inclined two-phase thermosyphons. While for the self-fabricated test sample (49 % filling ratio) heat transfer was limited by entrainment (temperature oscillations), dry-out phenomena (rise in temperature) occurred for the commercial solar heat pipe (16 – 25 % filling ratio) at 0° and 1°. This is in good agreement to the statement of Bezrodny & Podgoretskii [3], whereby thermosyphon operation is limited by dry-out if the filling ratio is too low while entrainment or flooding occurs if being too high. However, as both test samples have different geometry a direct comparison of filling ratio is not suitable.

While operating limit measurements of the commercial solar heat pipe showed good reproducibility, the detected operating limit of the self-fabricated one varied drastically. By re-running measurements after two months an influence of post-oxidation could not be observed. Moreover, no clear influence of step height and time in power increase on the measured operating limit value could be detected.

As the operation of the commercial solar heat pipe was limited by dry-out further investigations have to reveal if the poor reproducibility of entrainment limit arises from self-fabrication or the instability being the essence of entrainment. In this regard, especially the influence of the thermal boundary condition (temperature or power supply) on reproducibility has to be put into focus. Moreover, the influence of container and working fluid pretreatment, operating temperature and filling ratio on operating limit measurements has to be analyzed in future work.

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