Performance limitation effects and inconsistent conductance of heat pipes in solar collectors

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Introduction

Collectors with heat pipes are state of the art for non- or low concentrating evacuated tubular collectors (ETCs). They are already numerously tested and certified according to the Solar Keymark scheme rules. Solar collectors will be tested according to [EN 12975] and the collector power output will be described for a certain global irradiance level as a function of the heat gain and the temperature difference between ambient air and fluid. But it is possible that for heat pipe collectors in certain operation points this description can lead to wrong power curves, because of limitation effects within the internal heat transfer of the heat pipe. Depending on the construction of the heat pipe the power output of the collector for high irradiance levels can be a function of the collector fluid temperature instead of the temperature difference between ambient air and collector fluid.

At the Institut für Solarenergieforschung Hameln (ISFH an untypical power curve of a serial heat pipe collector type was determined. Additionally by means of a heat pipe test rig developed at the ISFH the performance data of the collector test were compared to the performance data calculated with the heat transfer limits of the single heat pipes used in the tested collector.

The performance limiting effects of heat pipes relevant for the collector test and the collector use in practice are shown in this section. It presents the determination of heat transfer limits of heat pipes and the impact of these limits on the power curve of a solar collector.

Collector performance measurement

A heat pipe ETC with 30 tubes within was tested according to EN 12975.

Therefore the efficiency η was determined at different temperature differences ΔT between the mean fluid temperature t_m and ambient air temperature t_a. The efficiency η is the ratio of thermal power output Q_{Gain} to irradiance power input $G{\cdot}A$. In figure 1 the power output of the collector area A is plotted over the temperature difference ΔT.

The results of the performance test show an untypical characteristic for lower temperature differences: At reduced temperature differences below 30 K the collector efficiency is getting lower than the efficiency at 30 K and the variation of the measurement points is getting higher. This power curve was reproducible and a further collector of the same type shows an identical behaviour.

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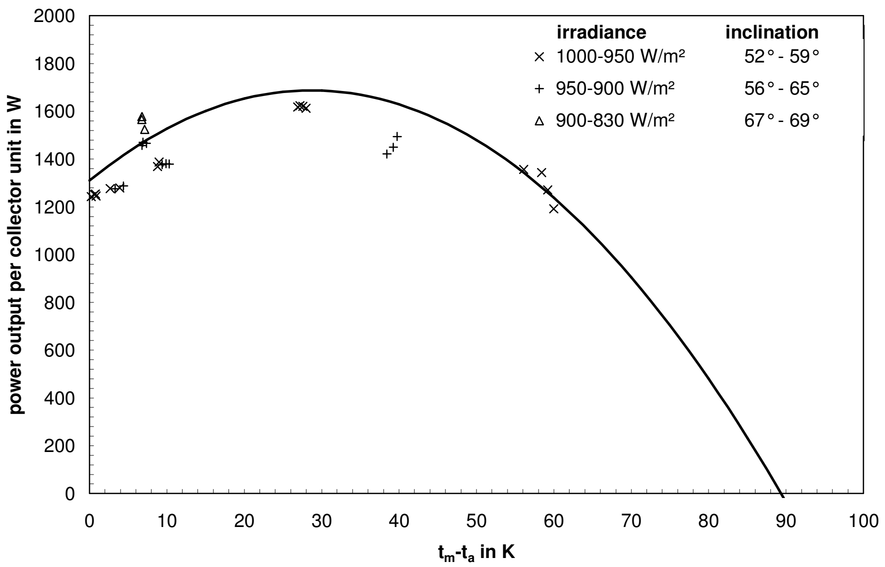

Figure 1: power curve according to EN 12975 for 1000 W/m² with measurement data related to the temperature difference ΔT

This characteristic is not explicable with an extraordinary behaviour of the thermal losses: There is no possibility that the heat loss coefficient of the collector insulation has a minimum at a defined temperature difference. Looking at equation 1 for the collector efficiency there remains the conversion factor □0 as the reason for the untypical efficiency curve.

$$A \cdot G \cdot \eta = A\left(G \cdot \eta_0 - a_1 \cdot \Delta T - a_2 \cdot \Delta T^2\right) \tag{eq. 1}$$

Having a closer look at the conversion factor in equation 2, we can concentrate our investigations on the thermal conductance u_{int}.

$$\eta_0 = (\tau\alpha)_{\text{eff}} \cdot F' = (\tau\alpha)_{\text{eff}} \cdot \frac{U_{\text{int}}}{U_{\text{int}} + U_{\text{loss}}} \tag{eq. 2}$$

The collector heat loss coefficient U_{loss} gets only marginally higher with an increasing temperature and the effective product of transmission and absorption $(\tau\alpha)_{\text{eff}}$ describing the optical losses of a collector is constant over the temperature. Provided that the flow conditions of the solar circuit is almost identical the thermal conductance U_{int} of a direct flow collector is nearly constant as well (a small increase with higher temperatures is typical). But this does not apply generally for heat pipe collectors.

Heat transfer limitations and thermal conductance of heat pipes

In collectors heat pipes are used for heat transfer from absorber to manifold. Inside of heat pipes a heat driven two-phase thermodynamic cycle takes place. Therefore, in the evaporator section of the heat pipe, which is located at the absorber, the working fluid is evaporated and transported to the condenser section, which is located at the manifold. Here the condensation takes place. Driven by gravity the condensate flows back into the evaporator section where it evaporates again. Typically in solar thermal collectors cost-effective gravitational heat pipes without capillary structures (two-phase closed thermosyphons) are used. Within collectors heat pipes function as highly concentrating heat exchangers based on the area ratio of the evaporator to the condenser. This specific characteristic has influence on the thermal conductance as well as the heat transfer limitations of heat pipes. Figure 2 represents an equivalent network of the mainly influencing thermal resistances on the overall thermal conductance of heat pipes.

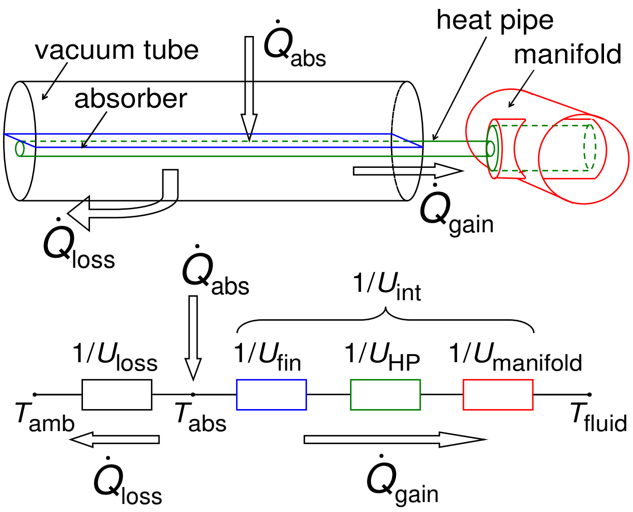

Figure 2: Node collector model for HP collectors

For heat pipe collectors the thermal conductance U_{int} can be split into partial conductances for the absorber U_{fin}, the heat pipe U_{HP} and the manifold $U_{manifold}$. In figure 2 is shown the sum of the inverse conductances – also called thermal resistances – in a node model. The thermal conductance of the absorber and the manifold are approximately constant, if the mass flow of the solar circuit not varies and if it occurs no transition of turbulent and laminar flow due to different fluid temperatures. Only the thermal conductance of the collector heat pipe U_{HP} varies with the useful heat path Q_{gain}, the inclination angle and the fluid temperature T_{Fluid} related on the collector (or the condenser temperature related on the heat pipe).

Especially the fluid temperature dependent heat transfer limitations of heat pipes are of interest. There are several physical effects, which limit the maximum heat transfer rate of heat pipes. The most relevant for heat pipes in solar collectors are the entrainment limitation and the dry-out limitation (e.g. [Faghri]). They are shown qualitatively in Figure 3. Due to heat transfer limitation at higher temperatures favourable stagnation temperature reduction of the collector may result and at lower temperatures critical performance reduction in the collector operation range is possible.

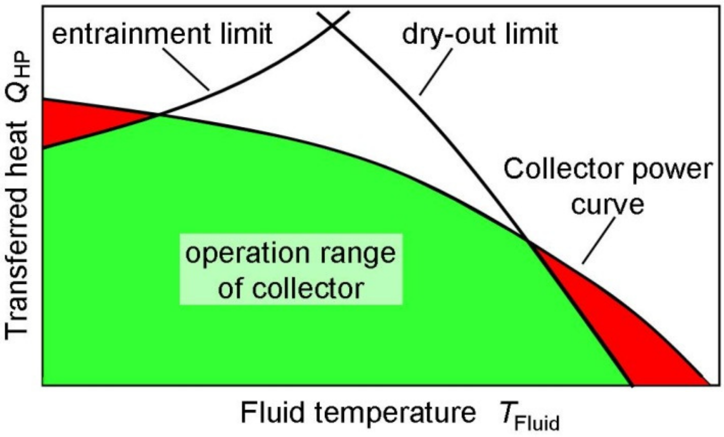

Figure 3: Qualitative heat transfer limitations of gravitational heat pipes

Dry-out limit

The dry-out limit will be reached at high operation temperatures. In this status the heat transfer is so high (or the filling ratio is so low) that all the working fluid of the heat pipe participates in the thermodynamic cycle and no fluid pool remains on the ground of the evaporator. With a further increase of the heat gain the heat pipe begins to dry-out and overheats from the bottom of the evaporator.

The stagnation temperature is reached if at the same time the heat loss flow of the collector is as high as the transferred heat of the heat pipe due to the high temperature level of the heat pipe. This is why it is possible to decrease the stagnation temperature of a collector with the dry-out limit [Mietkewitz].

Entrainment limit

The entrainment limit will be reached at low operation temperatures. It occurs, when the relative speed between flow of steam and condensate, and thus the surface shear stress is so large, that the up flowing steam dams or even carries along the down running condensate. As a result, not enough condensate flows back into the evaporator and the end of the evaporator runs dry.

Heat pipe test rig

For a detailed experimental investigation of the useful heat path of collectors with heat pipes, two test rigs were developed at ISFH. One test rig has been built up for measurements on heat pipes and the second one is a test rig to study the thermal transport properties of manifolds [Jack 2011]. The test rig for heat pipes is presented in the following.

In order to determine the heat transport capability of heat pipes, the test rig is equipped with an electrical heat source, which is placed directly at the evaporator section of the heat pipe. A fluid circuit connected to the condenser section is used as a heat sink. These two main components fluid circuit and insulated test case are shown in figure 4.

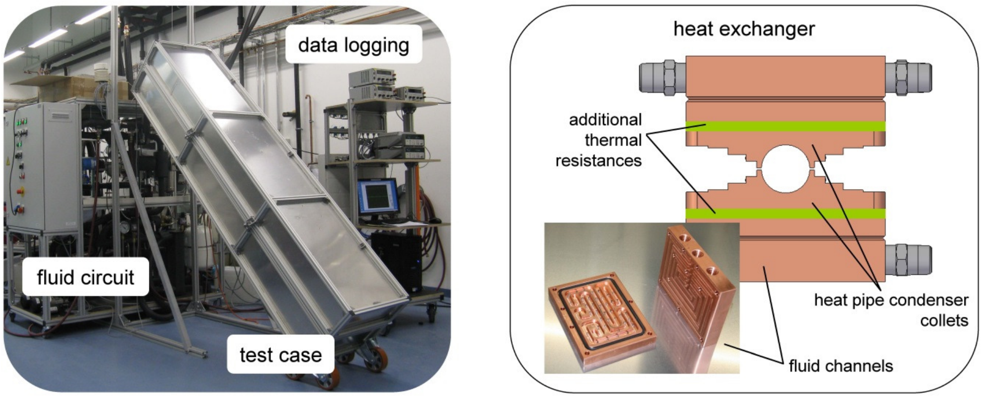

Figure 4: Complete heat pipe test rig (left) and heat exchanger between heat pipe condenser and fluid circuit with additional thermal resistances (right)

The fluid circuit is a high-pressure water circuit, which can be operated at temperature levels up to 180 °C. To determine the useful heat output transported via the fluid, a Coriolis flow meter with a measuring range of 5 to 300 kg/h is used. Thus, even very small outputs down to 10 W are measurable. To investigate heat pipes even at higher condenser temperatures than 180 °C, which is the maximum temperature of the fluid circuit, additional thermal resistances may be introduced as shown in figure 4. This way it is possible to increase the temperature of the heat pipe up to 400 °C [Schubert].

Heat pipe measurement

Using the test rig, the heat pipe's thermal conductance [U_{HP}] = W/K is determined as a function of the amount of transferred heat Q_{gain}, the condenser temperature T_{cond} and the inclination angle. The inclination angle, condenser temperature T_{cond} and evaporator temperature T_{evap} are set as boundary conditions. The heat transfer is measured calorimetrically within the fluid circuit.

By increasing the temperature difference between evaporator and condenser ΔT_{HP} the amount of transferred heat Q_{Gain} increases. Thus, the heat transfer can be enlarged up to the heat transfer limitation of the heat pipe. Reaching a performance limit is typically characterized by the considerable increase in evaporator temperatures at the bottom of the heat pipe. For this reason, over the length of the evaporator several temperature sensors are distributed uniformly as shown in figure 5.

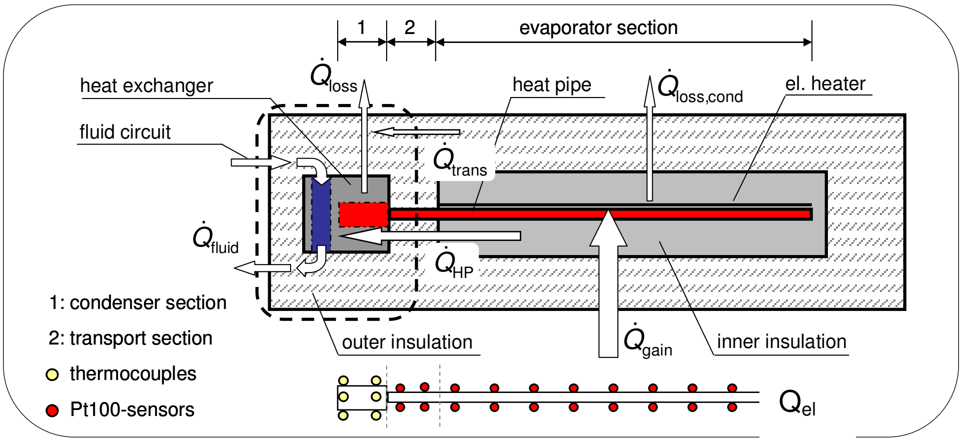

Figure 5: Schematically displayed heat flows inside the test case and positions of temperature sensors

By means of experiments, the two relevant heat transfer limitations can be distinguished, because in contrast to hitting the dry-out limit the entrainment limit leads to stochastically pulsation of evaporator temperatures. This effect is clearly measurable and is based on the fact that the interaction between steam and condensate near the entrainment limit behaves unsteady. Time-varying flow conditions occur since the damming of the condensate cannot be maintained quasi-stationary, thus resulting in significant temperature fluctuations as shown exemplarily in figure 6.

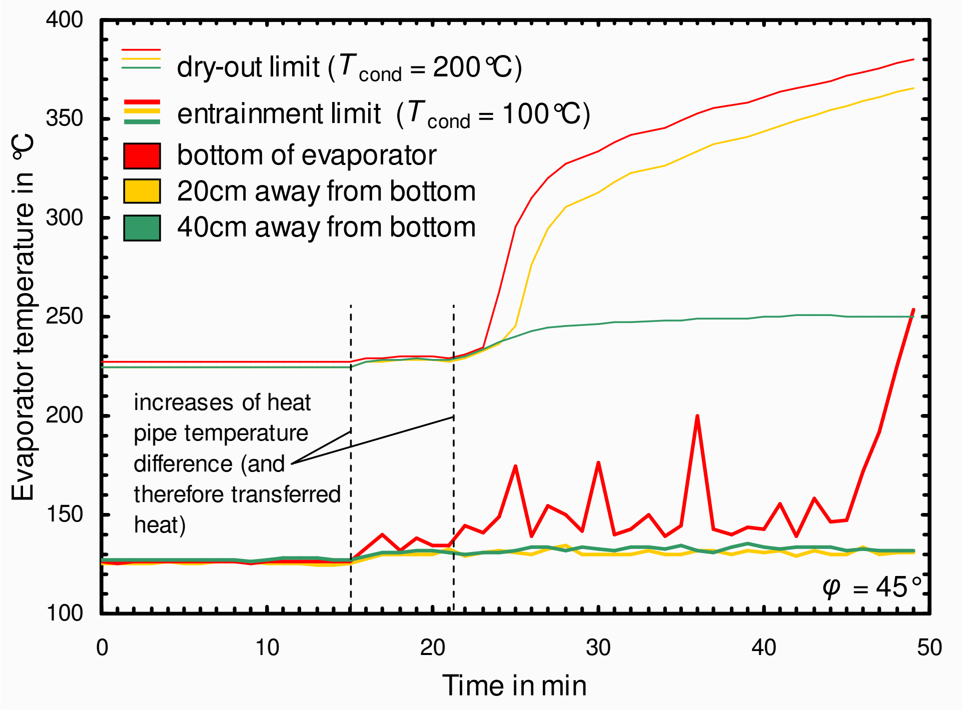

Figure 6: Time-dependent evaporator temperatures when hitting heat transfer limitations

Further rising of the evaporator temperature leads to extended drying of the evaporator and therefore to rising temperatures at the end of the evaporator (see right figure 7). Thus, the thermal conductance of the heat pipe is lowered, since the mean temperature difference between evaporator and condenser increases.

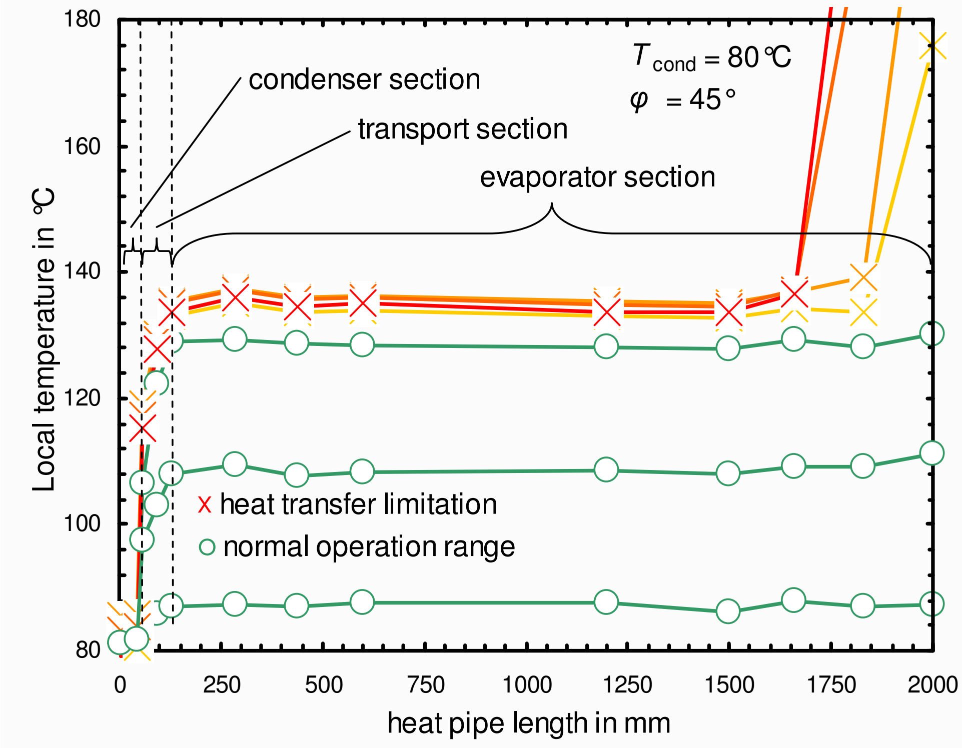

Figure 7: Increasing evaporator bottom temperatures due to dry out of evaporator

By varying the condenser temperature it is possible to determine the complete heat transfer limitations within the desired temperature range and thus the limit of the operating range of the heat pipe. Main influencing factor on the entrainment limit is the inner diameter of the heat pipe between evaporator and condenser (position of maximum vapor velocity, e.g. [Nguyen-Chi and Groll], [Bage]) and the main factors influencing the dry-out limit are the filling ratio and the type of working fluid (e.g. [Unk]).

With the presented experiments it was analysed if the untypical performance of the tested collector can be explained with the entrainment limit of the heat pipes. Figure 8 shows the entrainment limit and its beginning for the heat pipe of the tested collector. The beginning of entrainment is characterized by temperature fluctuations and a lowered thermal conductance U_{HP} but the transferred heat still increases with higher temperature differences between evaporator and condenser. The entrainment limit is reached, if no additional heat can be transferred. Thus the thermal conductance U_{HP} decreases on a very low level caused by the dry-out of the evaporator.

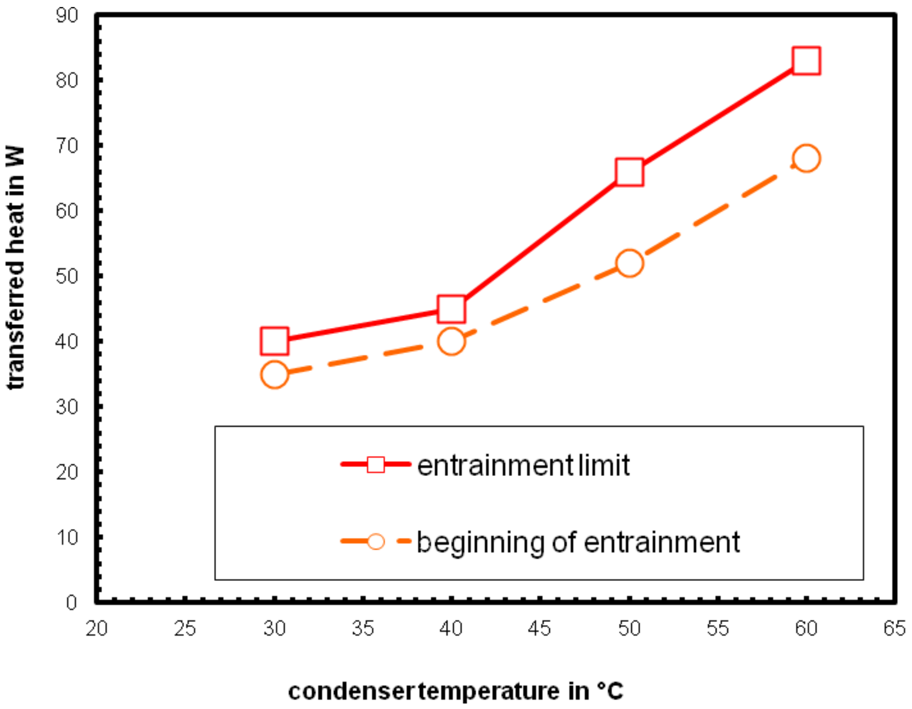

Figure 8: Determined entrainment limit of single heat pipe of the performance tested collector

In figure 8 the maximum heat transfer rates for 4 different condenser temperatures are displayed. Compared to other heat pipes the values are very low and indicate that the entrainment limit is responsible for the lowered collector performance at low temperatures. The construction and dimension of the heat pipe is identical to those of many other manufacturers, but such a low entrainment limit was never measured at comparable heat pipes. A possible explanation of these results is the existence of non-condensable gases in the heat pipe or the compound of the working fluid like water with a high fraction of antifreeze.

Description of collector performance with heat pipe limits

In order to compare the results of the heat pipe and the collector measurement a common scale basis must be found for the collector power curve. The entrainment limit depends on the condenser temperature and by means of a thermal conductance for the manifold the data can be referred on the fluid temperature. For the manifold construction of the tested collector a thermal conductance of 3.5 W/K was experimentally determined [Jack 2012]. Additionally it will be considered that the collector consists of 30 heat pipes in series. Therefore the corresponding fluid temperatures of the single heat pipes are differing between collector inlet and outlet temperature. As a consequence in figure 9 the entrainment limit and the beginning of the entrainment were displaced against each other about 3 Kelvin.

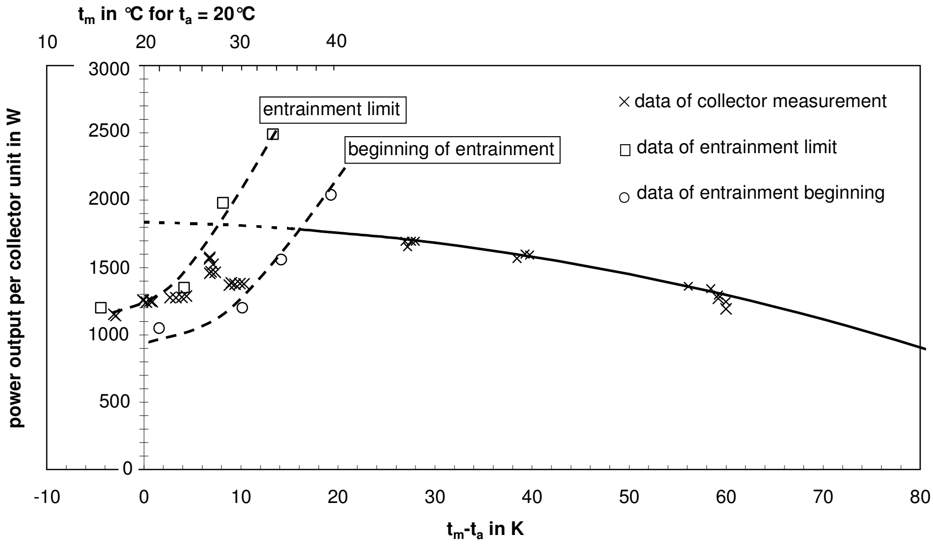

Figure 9: Power curve related on 1000 W/m^2 similar to EN 12975 with heat transfer limits for a ambient air temperature of 20°C and measurement points of the collector and the heat pipe performance test

In figure 9 the collector power curve according to EN 12975 and the measurement points beyond the transition zone of the entrainment limit are related on the irradiance level of 1000 W/m^2 and plotted over the temperature difference between mean fluid temperature t_m and ambient air temperature t_a. This dependence is not valid if the collector operates under conditions where the beginning of entrainment affects the collector performance. The entrainment limit is related exclusively on the fluid temperature. The measurement points of the collector performance inside the transition zone of entrainment limit must not be extrapolated to 1000 W/m^2 because of the limitation effect of the heat pipes.

Figure 9 shows that the transition zone of the beginning of entrainment and the entrainment limit correspond to the decreasing collector performance near the conversion factor. It demonstrates that in particular cases the performance of collectors with heat pipes can be partially limited by the entrainment limit of the heat pipes.

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