STAGNATION TEMPERATURE IN PVT COLLECTORS

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ABSTRACT: PVT collectors are thermal collectors in which a PV-laminate functions as the solar thermal absorber. In this way, a collector is generated that produces both heat and electrical power. A consequence of integrating a PV laminate in a thermal collector is a potentially high PV temperature, especially under stagnation conditions. In this paper, a numerical model to calculate this temperature is validated and estimates are made of the maximum PV temperature under stagnation conditions for various locations in Europe. It will be shown that for the prototype presented here, in the North of Europe the collector temperature will stay below 130 °C. This is important, since the risk of EVA delamination increases strongly for temperatures over 135 °C.
Keywords: PV Thermal, Encapsulation, Stagnation Temperature

1 INTRODUCTION

PV panels can become quite hot in the sun. In order to ensure the performance of PV laminates under increased temperature, PV laminates have to withstand 85 °C in thermal cycling and damp heat tests according to IEC 61215.

Recently, several articles have been published on the yield of PV thermal modules (PVT modules). In this type of module, the heat is actively withdrawn from the PV laminate. This increases the electrical performance of the PV and produces useful heat as well. Various designs have been published in which PV laminates have been integrated into thermal collectors, which would allow for a reasonably efficient heat production. A schematic representation is shown in Figure 1 and a manufactured collector in Figure 2 together with its measured efficiency curve.

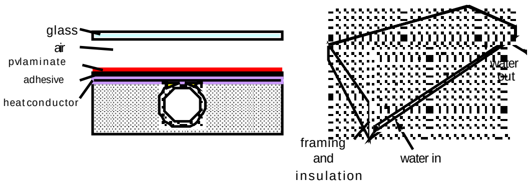

Figure 1: PV-thermal collector design.

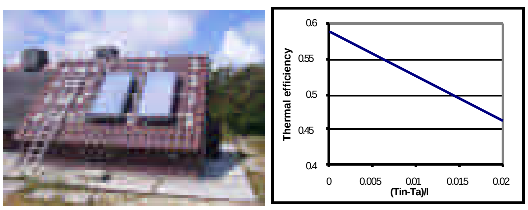

Figure 2: PVT collectors and measured thermal efficiency curve of the PVT collector

In normal operation of a PVT collector, the PV is cooled by the flow of the heat transport medium. However, if this flow fails, as regularly occurs in conventional thermal collector systems, the temperature in the collector can reach values over 120 °C. Since thermal cycling tests show that the risk of EVA delamination increases strongly for temperatures over 135 °C, the safety margins with respect to temperature are rather small. Therefore, it is important to obtain good insight in the temperatures to be expected under various ambient conditions. As a first order of magnitude guess of the stagnation temperature one can simply use the efficiency curve and find the value of the reduced temperature at which the efficiency is zero. This leads to:

$$\eta = F_R\left(\tau\alpha - U_L\left(T_{in}-T_a\right)/G_{pv}\right)=0 \Rightarrow T_{stag} \approx T_a + F_R\tau\alpha G_{pv}/\left(F_R U_L\right)$$

For the efficiency curve shown above, a combination of Ta = 30 ºC and I = 1000 W/m^2 leads to a stagnation temperature of 153 ºC. In reality, the stagnation temperature will be somewhat lower since second order effects have been ignored in this approach. However, the formula above shows clearly the dependence of the stagnation temperature on the ambient conditions. In addition, it shows that improvements in the collector efficiency directly increase the stagnation temperature.

2 MEASURED STAGNATION TEMPERATURE

In order to find out what temperatures will actually occur in an integrated PV-thermal collector, outdoor measurements of the collector stagnation temperature have been carried out in the ECN outdoor test-facility (in the North-West of Holland) under various ambient conditions. The collector temperature is characterised by two Pt-100 elements, one at the front and one at the rear of the PVT absorber. Since the heat is not actively withdrawn from the collector, the lateral temperature differences over the absorber are small. The ambient conditions are characterised by the measurement of instantaneous values of the ambient temperature, irradiance, sky temperature and wind velocity, all measured in the collector plane. The measured collector temperatures over the measurement period (May to August 2002) are shown in Figure 3.

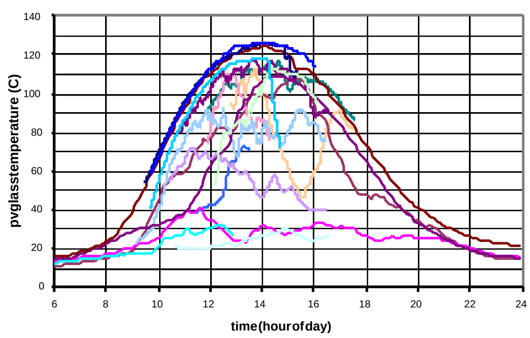

Figure 3: Measured stagnation temperature over various days, May-August 2002 (Ta 14 to 30 °C, v_{wind} 1 to 8 m/s)

It is clear from this figure that the stagnation temperature varies strongly between days, largely due to variations in the irradiance. In order to determine the relation between the stagnation temperature and the ambient conditions, the results for one day are shown in Figure 4.

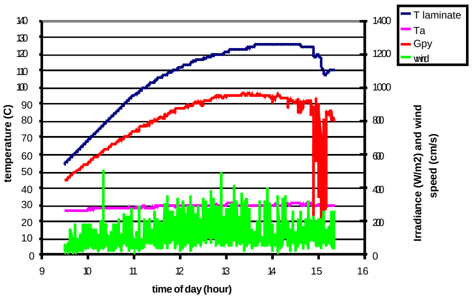

Figure 4: Stagnation temperature and ambient conditions measured on 29-7-2002.

This figure shows that a time lag exists between the maximum in the irradiance and the maximum in the stagnation temperature. In addition, it shows that a sudden drop in the irradiance does not lead to a similar drop in the stagnation temperature. Clearly, the characteristic time of the collector is essential in calculating a reliable value for an instantaneous value of the stagnation temperature. This characteristic time is related to the heat capacity of the collector, which is substantially larger for a PVT collector than for a conventional thermal collector.

3 TIME CONSTANT OF PVT COLLECTORS

A typical order of magnitude of the time constant of the PVT laminate can be found from the heat balance equation:

$$\Sigma c_p M \times \frac{\partial T_{PVT}}{\partial t} = \tau_\alpha IA - U_L (T_{PVT} - T_a) A - \dot{m} c_{p,water} (T_{PVT} - T_{in})$$

In this equation, the last term is an approximation, based on the assumption that the fluid leaves the collector with a temperature that is equal to the laminate temperature. Integrating this formula, one arrives at:

$$T_{PVT} = \left[T_0 - \frac{(\tau_\alpha IA + U_L T_a A + \dot{m} c_p T_{in})}{(U_L A + \dot{m} c_p)} \right] \times \exp\left[-\frac{U_L A + \dot{m} c_{p,water}}{\Sigma c_p M} t \right] + \frac{(\tau_\alpha IA + U_L T_a A + \dot{m} c_p T_{in})}{(U_L A + \dot{m} c_p)}$$

It follows that the time constant is of the order

$$\tau = \frac{\Sigma c_p M}{(U_L A + \dot{m} c_{p,water})}$$

For a flow of 75 litres per hour, this leads to a value of approximately 2.3 minutes. However, under stagnation (zero flow), this leads to a value of over half an hour.

4 THE NUMERICAL MODELS

The static model of the collector performance is described in Zondag et al (2002). The stagnation temperature could be calculated with this model by setting the flow rate equal to zero. In addition, a simple dynamic model has been built in order to calculate the stagnation temperature. The heat balance is given by the following three equations:

1. $$C \frac{\partial T_{cover}}{\partial t} = q_{rad} + q_{airgap} - q_{sky} - q_{wind}$$

in which $C = V_{glass} Cp_{glass} \rho_{glass}$

2. $$C \frac{\partial T_{PVglass}}{\partial t} = (\tau_\alpha - \eta_{el}) G - q_{pvabs} - q_{rad} - q_{airgap}$$

in which $C = V_{glass} Cp_{glass} \rho_{glass} + V_{EVA} Cp_{EVA} \rho_{EVA} + V_{Si} Cp_{Si} \rho_{Si}$

3. $$C \frac{\partial T_{absorber}}{\partial t} = q_{pvabs} - q_{back}$$

in which $C = V_{sheet} Cp_{copper} \rho_{copper} + V_{tube} Cp_{copper} \rho_{copper} + \frac{1}{2} \times V_{ins} Cp_{ins} \rho_{ins}$.

The heat flows are all calculated from the previous set of temperatures and are then inserted into the equations above to find the temperature at the present time step. The starting values for laminate temperature is the measured laminate temperature. The starting value for the cover temperature is the mean value of the laminate temperature and the sky temperature.

Next, the measured stagnation temperatures have been compared to the results of this model. Two days have been analysed in depth: a day with a clear sky and a day with a cloudy sky and a corresponding variable irradiance. The results are shown in Figure 5. In order to visualise the effects of the heat capacity, the results are calculated both for the real heat capacity of the prototype and for a lower heat capacity (25% of the real value).

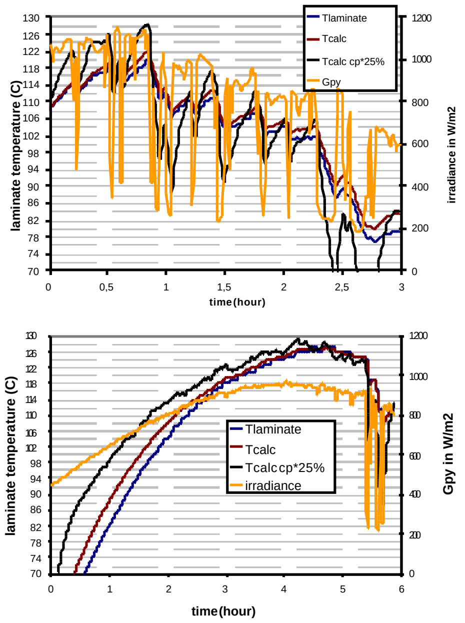

Figure 5: Comparison of calculated and measured laminate temperatures together with ambient conditions on a cloudy day (upper figure) and a clear day (lower figure).

Figure 5 shows that the model with the proper heat capacity resembles the measurements within roughly 2 °C. For the model with the reduced heat capacity, however, it can be seen that the discrepancies between the data and the model increase to values as large as 3 °C for the clear day and 20 °C for the cloudy day. This result clearly shows that the use of a static model (which has an effective heat capacity of zero) will lead to large discrepancies between measured and simulated data.

Cp glas	840 J/kgK	$\tau\alpha$	0.765
Cp EVA	2300 J/kgK	h_{back}	1.0 W/m^{2}K
Cp copper	390 J/kgK	ε_{glass}	0.85
Cp insulation	840 J/kgK		

Table 1: model parameters

The model can now also be used for a sensitivity analysis. The dynamical program was used to find the reduction in the stagnation temperature with a change in ambient conditions. The results are shown in Table 2. Since the conditions were set fixed over the day, the resulting temperatures are too high for a real case, but the trends are clear. It can be seen that the irradiance and the wind speed have a significant influence, while the effect of the ambient temperature is somewhat less.

conditions	Tstagnatio n
Base case (Gpy = 1000 W/m^2, Ta=30 °C, Tsky=15 °C, vwind=1 m/s)	130.4 °C
Gpy = 1000 →900 W/m^2 in base case	122.2 °C
Ta = 30→25 °C & Tsky=15 →10 °C in base case	127.1 °C
Vwind = 1 →2 m/s in base case	123.9 °C

Table 2: Sensitivity to ambient conditions

5 CALCULATIONS WITH AVERAGED DATA

In the preceding paragraphs it has been shown that a dynamical model using instantaneous data of the ambient conditions can give a very reliable estimate of the instantaneous value of the stagnation temperature. Unfortunately, ambient data with a 10 second time base are seldom available. Test reference years and other climate years are conventionally averaged data on an hourly basis, which means that all peaks in the climate data are averaged away.

However, for the calculation of maximum temperatures this does not need to present a problem, since Figure 3 shows that the highest values of the measured stagnation temperature were found on clear days which have a smooth variation of the irradiance. Next, due to the time constant of the collector, short peaks in e.g. the irradiance will not lead to similar peaks in the stagnation temperature. In order to visualise the effect of the averaging interval, the response of the dynamical model using time averaged values to a step function in the irradiance was calculated. The model makes use of a running average of the ambient data and the calculation is done for either no averaging interval or an averaging interval of 1 hour. The result is shown in Figure 6.

Next, the stationary model was taken into account. It was argued before that a stationary model can not accurately calculate the instantaneous value of the stagnation temperature using instantaneous values of the ambient conditions. However, if hourly averaged data are used a stationary model can be expected to be almost as good as a dynamic model, since the averaging interval is longer than the time constant. The stationary model and the dynamic model were compared for their response to a step function in the irradiance. The result is also shown in Figure 6. Due to the averaging the resemblance between the dynamical and the static model is strongly increased.

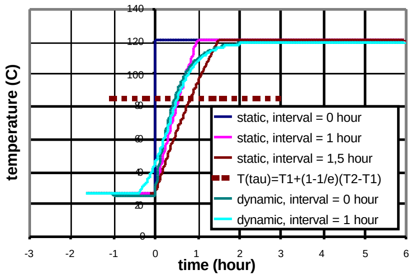

Figure 6 The effect of the averaging interval over a step function as compared to the dynamic model

Finally, the RMS of the temperature difference between simulated and measured temperatures for a clear day and a cloudy day are shown in Figure 7 as a function of averaging interval. This figure clearly shows that the accuracy of the dynamic model is larger than the stationary model. At the other hand, the accuracy of a steady state calculation strongly increases if the data are averaged over a certain interval that is of the order of magnitude of the time constant of the collector. For the present applications it seems that an averaging interval of 1 hour is close to an optimum. The figure shows that the accuracy is better for a clear day in which the ambient conditions change more smoothly in time than for a cloudy day (the minimum in the curve of the cloudy day is much higher than the minimum in the curve of the clear day).

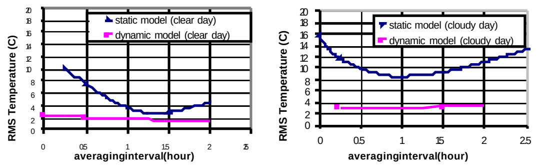

Figure 7: The effect of the averaging interval on the RMS value of the difference between the measured and the calculated stagnation temperature, using a steady state model or a dynamic model.

Two important conclusions should be drawn. First of all, the inaccuracy resulting from stationary calculations is still substantially larger than the inaccuracy resulting from the dynamical model. It seems worthwhile, therefore, to calculate the stagnation temperature using a dynamical model. Nevertheless, the inaccuracy of the static model is strongly reduced if hourly averaged values are used. Secondly, it turns out that the dynamical model is not very sensitive to the averaging interval, which means that a reliable estimate of the maximum stagnation temperature can be made on the basis of hourly averaged data. These conclusions are the basis for the climate studies in the next paragraph.

6 CLIMATE STUDIES

Since climatic conditions vary over the world, the chance of finding stagnation temperatures in the critical range is not the same everywhere. In addition, the collector angle has consequences for the stagnation temperature; the largest stagnation temperature occurs when perpendicular incidence occurs at 13:00 during the summer (highest ambient temperature), which gives for De Bilt, Tours and Sevilla respectively 28.4°, 23.8° and 12.8° collector angle.

Four different locations have been evaluated for a collector angle of 45° using data generated with the clear-sky option in the computer program Meteonorm. In the climate years generated by Meteonorm, one day was selected with the largest irradiance on the collector plane. The ambient conditions of these days for the various locations (De Bilt in the Netherlands, Tours in France, Sevilla in Spain and Ouagadougou in Burkina Faso) are summarised in Figure 8. In the calculations, the irradiance and the temperature indicated in Figure 8 were used. The wind speed was set to a fixed value of 1.5 m/s because of the fact that the wind speed over the collector is often significantly below the value in the free field.

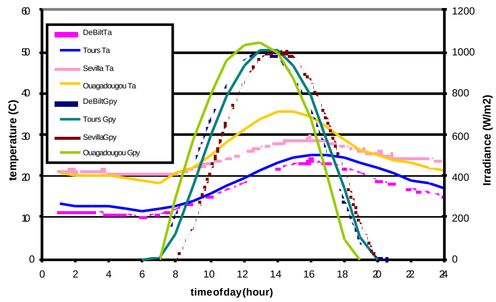

Figure 8: A day with maximum irradiance on the 45°-plane in four different countries.

This leads to the values presented in Table 3. In this table, the maximum yearly stagnation temperature is calculated based on a clear-sky year. It can be seen that the static model overpredicts the stagnation temperature by roughly 3 °C. In addition, the table also presents the maximum stagnation temperature calculated on basis of the 10-year maximum values of the irradiance and the temperature as calculated by Meteonorm. In the calculated climate year, the day was selected with the combination of irradiance and temperature that would lead to the largest value of the stagnation temperature. An indication that these results are reliable, is the fact that the maximum stagnation temperature measured in our experimental set up in the Netherlands over a period of two years was 124 °C in 2001 and 126 °C in 2002, which is in the same range as the values presented here. Finally, the temperatures are also indicated for the case in which the PV converts part of the irradiance into power. This lowers the stagnation temperature by roughly 5 °C.

location	Static Clear sky	Dynamic Clear Sky	Dynamic 10 year max	Dyn 10 year max + PV
De Bilt	123°C	120 °C	129 °C	124 °C
Tours	124.°C	122 °C	128 °C	123 °C
Sevilla	128 °C	126 °C	137 °C	132 °C
Ouagadougou	135 °C	132 °C	145 °C	140 °C

Table 3: Calculated stagnation temperatures (laminate orientation due south, 45 ° angle with horizon)

Finally, a frequency plot of the stagnation temperature was made with the dynamic model. The results are displayed in Figure 9.

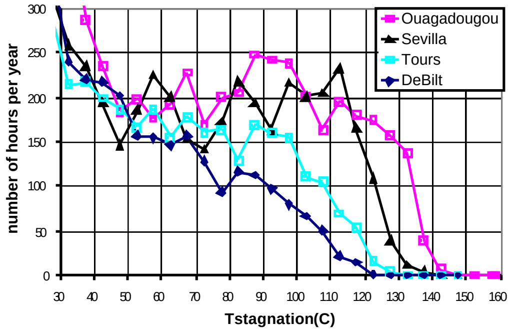

Figure 9: Stagnation temperature frequency plot (in intervals of 5 C) for different locations, as calculated with the dynamical model using Meteonorm data.

7 CONCLUSIONS

It can be concluded that in the North of Europe the stagnation temperature of the present PVT laminate mounted under 45 ° will stay below 135 °C, which means that direct delamination of the EVA is not to be expected. Closer to the equator, the safety margins might be exceeded, however. It has been shown for the case of Ouagadougou that delamination should be expected here.
This does not mean that the problem in Europe can be ignored. It should be realised that with increasing efficiency of the PVT laminate, e.g. by increased absorption or by reduced radiative or convective losses, the stagnation temperature will become correspondingly higher and can be expected to lead to serious problems for the application of EVA. In addition, the effect of the mounting angle of the collector is also of importance.
Although in Europe the temperature of the present PVT stays below 135 °C, the margins are small. In addition, the EVA is increasingly susceptible to yellowing under the combination of high temperature and UV, while temperatures of this magnitude certainly put an additional strain on the PV-laminates that might shorten their life time.
As a final remark, one should realise that stagnation is of infrequent occurrence, and will not often coincide with extreme radiation and temperature conditions. However, this chance also depends on the design of the system. It should be kept in mind that for domestic hot water systems, stagnation typically occurs during summer holidays in which high stagnation conditions might well occur. Clearly, the stagnation temperature should be a point of attention.

8 LITERATURE

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