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The Night Cooling Effect on a C-PVT Solar Collector

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Abstract

Night cooling consists in running a fluid through a solar panel during the night in order to reduce the fluid temperature which can be used for cooling applications. Radiative heat losses can allow the fluid to reach temperatures below ambient while conduction and convection works to equalize the collector with the ambient temperature.

This paper analyzes the possibility of using an asymmetric concentrating photovoltaic thermal solar collector (C-PVT) for cooling applications during the night by losing heat through convection, conduction and irradiation. The cooling performance of the C-PVT collector has been measured during the night at different inlet temperatures in the interval of 13 to 38°C which corresponded to a ΔT (between the collector average and the ambient) from 6 to 28°C.

The performance of the tested C-PVT collector has been measured at different inlet temperatures in an interval of 13 to 38°C. During all performed measurements, the radiation losses did not drive the collector temperature below ambient temperature. With high ΔT (between the inlet and the ambient) of 30°C, a 1,85°C temperature decrease in the fluid was obtained. For ΔT of 14°C, the temperature decrease was only 0,88°C. The measurements showed a night U-value for the Solarus C-PVT of 4,2 W/m^2K This correlates well with previous papers showing measurements taken during the day.

Heat losses seem to be dominated by convection and conduction due to the existence of the glass in the collector. Despite this, a measurable relation between heat losses and cloudiness factor exists. This shows that the irradiance losses are not negligible.

Only very specific applications can be suited for night cooling with this collector design, since it is not so common to have applications that require low grade cooling during the night time or justify storing this energy. However, if the C-PVT design was made without a glass cover, the results could potentially be very different for locations with many clear nights.

Keywords: *Concentrating PVT, CPC-collector, Asymmetric Collector, Collector Testing, Night Cooling*

1. Introduction

All objects are exposed to energy flows at all times. Some flows increase the energy level of the object while others decrease and are called energy losses. Energy losses of thermal energy are called heat losses and they occur by three different processes: Conduction, Convection and Irradiation.

Any two materials that are in contact and have different temperatures transfer heat between themselves in the direction of the material with a lowest temperature. This process is called heat conduction and can be calculated with the law of Fourier:

$$\dot{q} = -k\frac{\delta T}{\delta x} \qquad \text{(equation 1)}$$

where k is the heat conductivity and $\frac{\delta T}{\delta x}$ the temperature gradient. In a flowing fluid, it also occurs an energy

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transport which depends on the velocity and the level of turbulence, thus on macroscopic movements. This transport is called heat convection and is calculated together with the heat conduction:

$\dot{q} = \alpha \cdot (T_1 - T_2)$ (equation 2)

where α is the heat transfer coefficient which comprises fluid parameters, flow parameters and geometric parameters, and $(T_1 - T_2)$ is the temperature difference between the interacting systems.

The heat radiation denotes the electromagnetic waves which a body emits to its environment on the basis of its temperature. The maximum radiation density of a body is calculated by:

$\dot{e}_S = \sigma \cdot T^4$ (equation 3)

and is emitted by a so called blackbody (VDI, 2013).

1.1. The Basics behind Night Cooling

During the day, the losses described above are generally lower than the amount of incident solar radiation on the collector and, thus the collector gains energy. However, during the night, since the solar radiation is zero, the energy intake is smaller than the heat losses, which leads to a decrease of the collector temperature. This effect is called night cooling.

For being able to cool during the night two main factors are considered in this paper. One is the cooling on the basis of convectional and conductional heat losses while the other is called night sky radiative cooling.

The heat losses caused by night sky radiative cooling are done by a radiative process which can be separated in two sub processes: One is the radiation from the earth to the clear sky. This can be assumed as a black body radiation whereby the temperature of the black body is giving the surface temperature of the earth or in this case the collector. The other process is the atmospheric radiation caused by water vapor, carbon dioxide and ozone (Armenta-Déu et al., 2003).

Heat losses caused by convection and conduction will cool down the fluid in the collector to no more than the ambient temperature. On the other hand, radiative cooling is able to decrease the temperature level of the fluid below the ambient temperature, if the surface is an adequate emitter. In this way, the fluid gains heat during conductional and convectional heat exchanges (Dobson, 2005).

One final note should be made comparing PVT to standard thermal collectors. PVT panels can go below ambient temperature. This is considerably more difficult in thermal. This is because the PV cells emit much more radiation than the selective surface. Basically, a worse performance during the day by PVT collectors, leads to a better performance in cooling during the night. It is not reasonable to expect to have a panel that performs well in gaining heat during the day and, at the same time, also performs well at loosing heat during the night.

1.2. Possible Applications for Night Cooling

Since night cooling can be able to provide fluid temperatures below the ambient temperature, it can be used to decrease the temperature of materials below the ambient temperature. Three main constrains are limiting the applicability of night cooling: The first constrain is relatively small amount of cooling energy. The second constrain is the small temperature difference to the environment which significantly limit its range of applications. The third constrain is that in cloudy nights, the cooling energy gained will be at best at ambient temperature.

According to Armenta-Déu et al. (2003), possible applications for night cooling are production of fresh water, freezing and food preserving as well as building air-conditioning and energy generation. All of these applications sharing the need of cooling energy, the differences are the temperature ranges and the amount of energy required.

One way to make a night cooling system can be to, during the night, use a normal heating system but this time with the goal of losing heat. Therefore, the fluid would flow through the collector, cool down and gain energy while passing the heat exchanger. The heat exchanger brings the low temperature energy flow to a thermal storage which will decrease its temperature level during the operation time. The lower the temperature level reached, the more possible applications can be suitable. However, the temperature level is depending on the heat losses of the module, thus if the operating temperature drops under the ambient temperature (due to night sky radiative cooling), the thermal storage could reach a rather low temperature levels.

Another possible application is to use the cooling energy for phase change of PCM (phase change materials). These materials can be used in buildings for cooling during the day. They can be mounted on the ceiling to take the heat during the day to change its phase and thereby cool down the room temperature. During the night with heat losses to the environment and without energy gain from the sun the room temperature decreases and the PCM starts to change back its phase to its previous phase. The cooling energy from the collectors could be used to cool down a bigger area of PCM increasing the potential benefit from this application.

A practical implementation of the above described could be to run the thermal cycle of the collector in the standard way and to attach a heat exchanger. The second thermal cycle could be gaseous and directly blown to the consumer, in this case, the PCM. It could also be a liquid which circulates to the PCM in a pipe system. Additionally, other applications which need space cooling, like rooms for computer servers, show potential (Armenta-Déu et al., 2003).

2. Collector Description and Method

This chapter describes the used testing equipment and system as well as the asymmetric C-PVT collector.

2.1. The Test Setup

The Solarus C-PVT collector has been placed on the rooftop of the university in Gävle, Sweden, and faced to the south with an angle of 60 degrees. The collector total surface is 2.4 m^2 divided between two throughs each with one receiver. Each receiver holds strings of cells on both sides. This strings are either 19-19-19-19 or 6-32-32-6 cell as detailed in Fig. 1 and Figure 3. The collector stand holds a Kipp & Zonen solar radiation sensor at the same tilt as the collector.

Fig. 1: Solarus C-PVT collector and solar radiation sensor

Fig. 2: Thermal system

The thermal system features two loops. In the primary loop, a fluid (water), is passed through the collectors and then to a heat exchanger. This loop is separated in two sub loops, one for each collector through. Each sub-loop has its own Kastrup flowmeter but only one pump is required to run the two sub-loops. An expansion valve is placed in the circuit for safety as shown in figure 2. At the entry and exit of the collector, four PT100 temperature sensors are installed, as show in figure 1. The primary loop also features a small tank for mixing the water and a heater which allows regulating the inlet temperature. This heater can be used in conjunction with the secondary loop. The secondary loop is merely grid water flowing through the heat exchanger in order to reach lower inlet temperatures. Both the heater and the grid water are designed in order to keep the inlet temperature as steady as possible. A picture of the thermal system is shown in figure 2. The pumps in the thermal system in figure 2 circulate the water to the collector (shown in figure 1) and back.

2.2. Solarus C-PVT collector

The Solarus C-PVT collector design is called Maximum Reflector Concentration (*MaReCo*) and belongs to a family of stationary reflectors patented by the Swedish company Solarus. The reflector has a parabolic and circular shape and is used to concentrate the solar radiation. The reflector is made of anodized aluminum with a total solar reflectance ρ_{total} of 95% (measured according to norm ASTM891-87). A reddish brown silicone is used for electrical insulation between the mono-crystalline PV cell and the receiver core on both the upper and lower side (Gomes et al., 2013).

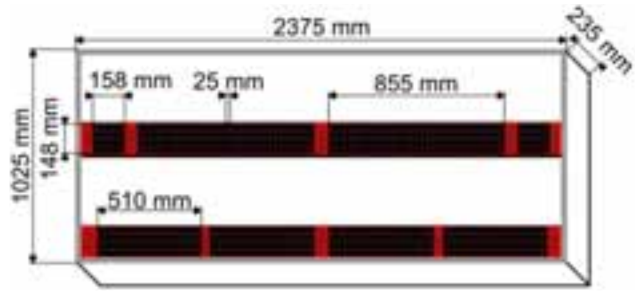

Figure 3: Test module dimensions

The module contains a glazed protection which is made of low iron tempered glass with a solar transmittance τ_{glas} of 95%, measured according to the norm ISO9050 (Giovinazzo et al., 2014) and a supporting structure manufactured out of plastic and metal (Gomes et al., 2013). The efficiency for direct light η_{direct} of the collector reaches 70%, while the efficiency for diffuse light $\eta_{diffuse}$ is 50.8%. Furthermore, the linear loss coefficient a_1 is 4.484 W/(m^{2}K) and the secondary loss coefficient a_2 is 0.0034 W/(m^{2}K) (Gomes et al., 2013).

3. Results and Discussion

For testing the performance of the Solarus C-PVT collector, measurement values from 18 nights between the 5th of September and the 2nd of November of 2014 have been analyzed. Table 1 comprises the night with the maximum (05.09. – 06.09.), average (09.09. – 10.09.) and minimum (28.10. – 29.10.) energy gain, as well as the results of a night in which an electrical heater provided a steady inlet temperature of 40°C (09.10. – 10.10.). The night time period is defined to be between 10PM and 05AM. Appendix 2 contains a wider collection of the measured night.

The following rows of the table show the cooling energy obtained, E_{cold}, in [kWh], the specific heat removal rate $\dot{e}_{cold} = \frac{\dot{E}_{average}}{A}$ in [W/m^2] (with the average energy gain during the night $\dot{E}_{average}$ and the surface area of the module A), the outlet temperature T_{out} in [°C], the ambient temperature T_{amb} [°C], the temperature difference between outlet and the inlet of the collector ΔT [°C], the temperature difference between collector average and ambient $T_{coll} - T_{amb}$ [°C], the cloudiness factor in [%] and the wind velocity v_{wind} [m/s]. The data for cloudiness and the wind velocity have been obtained from the database of the World Weather Website, which contains values for every third hour which have been taken for the time period between 10PM and 05AM and were averaged.

The measurement results show that the circulating water through the collector during the night can lose up to 2 kWh of thermal energy with an average power of more than 60 $\frac{W}{m^2}$. However these values are highly dependent on a number of conditions being met.

Table 1: Results night cooling measurement data

Night [22:00 – 05:00]	E_{cold} [kWh]	$\dot{e}_{cold}$ [W/m^2]	T_{out} [°C]	T_{amb} [°C]	ΔT [°C]	$T_{coll} - T_{amb}$ [°K]	Cloudiness [%]	v_{wind} [m/s]
05.09. - 06.09.	-1,08	-63,75	23,0	10,2	-0,88	13,2	5,3	2,1
09.09. - 10.09.	-0,72	-42,23	18,7	8,6	-0,58	10,5	40,7	1,8
09.10. - 10.10.	-2,0	-117,34	35,8	8,7	-1,85	28,1	88,7	1,8
28.10. - 29.10.	-0,44	-25,79	18,6	12,74	-0,37	6,0	54,3	6,7

With a decrease in temperature of less than 1°C few applications are feasible. However, the measurement system is not made for storing the water, thus the water has been cooled down in every loop to about the same temperature.

Table 1 shows that one of the main factors in the night cooling effect of the Solarus collector is the difference between inlet and ambient temperature, as show in table 1. As expected, the larger this difference, the higher the cooling power gained during that night. This is show clearly in figure 4.

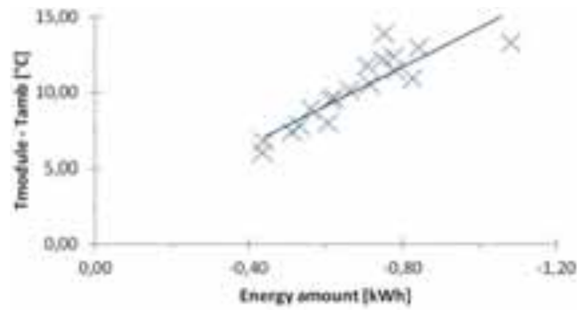

Figure 4: Cooling Energy Collected vs ΔT (Average Collector Temperature – Ambient Temperature)

During a clear night, the exchange of radiation between the collector and the sky is cooling down the collector. This way, clear nights are expected to increase heat losses. For some collector designs, this effect can be so strong that allows the collector to reach temperatures below ambient.

The measurement results listed in Table 2 in appendix can be visualized in Figure . These results show an increase in the collector heat losses when the cloudiness level is reduced. Consequently, it is not just the impact of conductional and convectional heat losses which accounts for the decrease in the fluid temperature.

The cloudiness was expected to correlate to the ambient temperature but our study in Figure **Error! Reference source not found.** did not show a clear dependency between ambient temperature and cloudiness.

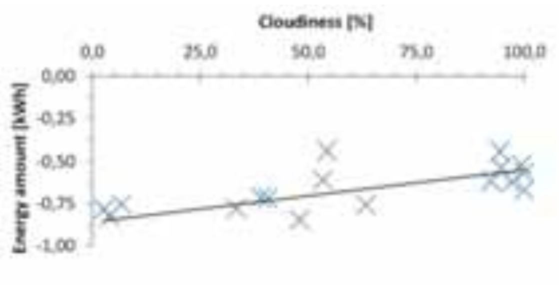

Figure 5: Impact of cloudiness on heat losses

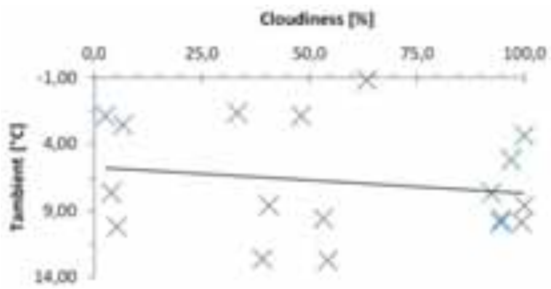

Figure 6: Impact of cloudiness on ambient temperature

In figure 7, we analyze the dependency between the cooling amount gained and the wind velocity. An increase in wind velocity is expected to directly lead to an increase in convective heat losses. However, our measurement results shown that the heat losses are decreasing with an increasing wind velocity. This is result is an error that may be a result of the fact that the wind measurements were not done exactly in the same location where the collector night cooling power was measured. Nevertheless, these results suggest that the convectional heat losses have a lower impact on the Solarus C-PVT collector than the losses caused by conduction and radiation or, in other words, the effects of the wind velocity is less significant that other factors.

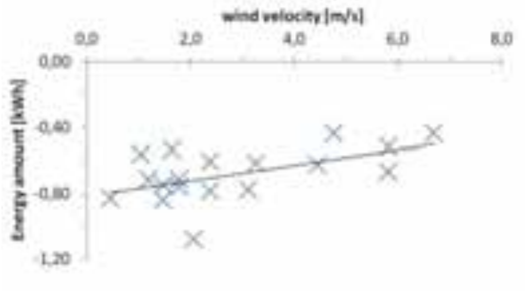

Figure 7: Impact of wind velocity on heat losses

For calculating the amount of cooling energy caused by night radiative cooling several equations are introduced for the sky temperature as well as the sky emissivity (Eicker et Dalibard, 2011). Most of these equations require temperature and pressure parameters which haven´t been measured. Two equations are just depending on the ambient temperature but Eicker et Dalibard (2011) show that the achievable results are fitting inaccurately with the measurement values and are thus not presented.

On the other hand, heat losses caused by conduction and convection can be calculated and subtracted from the entire amount of cooling energy. This method requires accurate values for the wind velocity. Previous consideration values for the wind velocity have been taken from a weather website, which is accurate enough for general statements but not for an accurate calculation of convectional heat losses.

Fig. shows the impact of cloudiness on the obtained cooling power per square meter, as well as the temperature difference between the module average and the ambient. For this graph, we have defined low cloudiness has being smaller than 7%, medium cloudiness between 40% and 60% and high cloudiness bigger than 90%. All measurements in this figure are done on an interval of the temperature difference between 7.5°C and 12.5°C where a more or less linear dependency can be seen for the impact of cloudiness. Furthermore, since many points overlap on the graph, an average of the three points (low, medium and high cloudiness) is also shown in the figure. These three points clearly show an increasing temperature difference with a decreasing level of cloudiness.

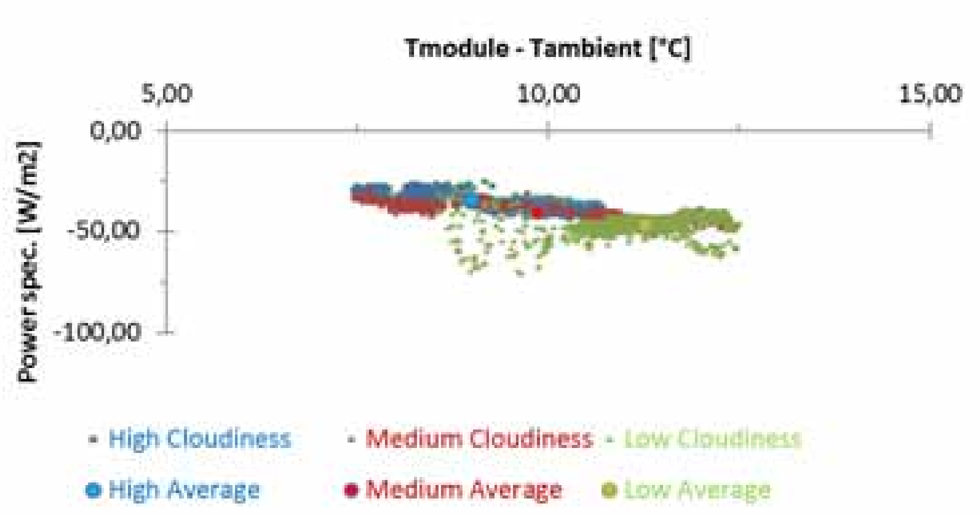

Fig. 8: Impact of cloudiness on power and temperature difference

Figure 9 shows the collector specific power loss during the night. The points measured at higher temperatures difference (inlet=40ºC) display a large spread due to the fact that the available thermal test system was not able provide a sufficiently stable temperature. This factor was combined with a relatively low thermal mass of the receiver. Despite this equipment issue, it is still fair to say that the collector night U-value is close to 4.2 W/m^{2}K since there is an acceptable R^2. The U value is given by the slope of the figure 9.

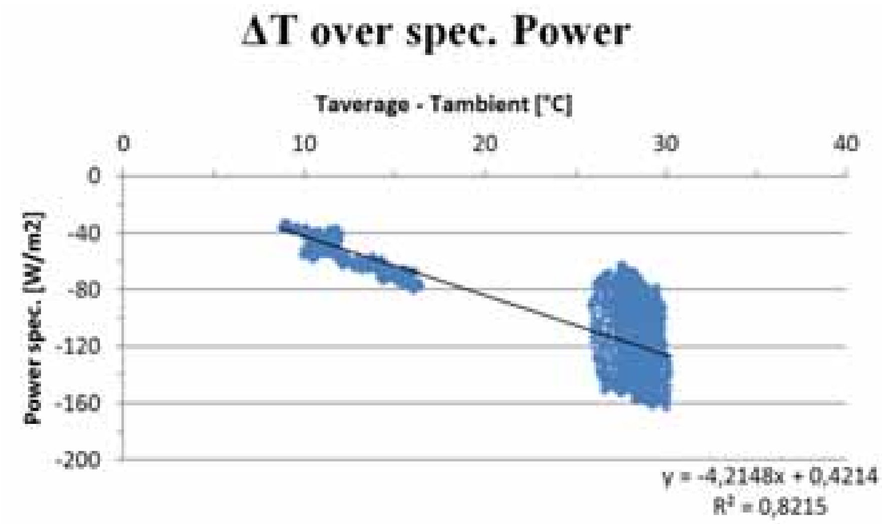

Fig. 9: Specific Power vs ΔT (Tcollector – Tambient)

Table 3 shows the result of annual simulations during the day and compares with the results of the night measurement results. It is important to note that the night cooling results are an extrapolation from an average of the nights (at 6 or 10 C above ambient temperature) to an annual output. The daily simulations were created using the Solarus simulation software. The cooling power obtained is not negligible but the issue remains how to use cooling power above ambient temperature.

Additionally, a comparison between the energy spent in pumping and the cooling gained should be performed.

Table 3: Comparison of annual output of the C-PVT in Stockholm.
Outputs in kWh/m2/day and the temperatures in ºC. Tmed is the collector average temperature.

	During the Day			During the Night	
Location: Stockholm	**Tmed-Tamb**	**Heating**	**Electrical**	**Cooling**	**Tmed-Tamb**
Extracting heat at an average of 30C above Ambient	30	1.06	0.22	0.20	6
Extracting heat at an average of 70C above Ambient	70	0.38	0.16	0.33	10

4. Conclusion

The performance of the tested C-PVT collector has been measured at different inlet temperatures in an interval of 13 to 38°C.

The factor with the highest impact in the night cooling effect of the Solarus collector is the difference between inlet and ambient temperature, as show in table 1 and 2 as well as figure 4. This implies that only very specific applications can be performed since it is not so common to have applications that require low grade cooling during the night time or justify storing this energy.

During all performed measurements, the radiation losses did not drive the collector temperature below ambient temperature. In nights, when the heater was not used to keep the inlet temperature steady, the collector temperature could be decreased by a maximum of 14°C during the whole night.

In some night, the heater was used to keep the inlet temperature steady, this leads to higher cooling energy gains being registered over the night, since we are losing energy that is provided by the heater. With high ΔT between the inlet and the ambient, as is the extreme case of a ΔT of 30ºC, a 1,85ºC temperature decrease in the fluid was obtained and recorded throughout the night. However, for ΔT of 14ºC, the temperature decrease was only 0,88ºC.

Still, the relatively low impact of cloudiness shown in figure 5 and 8 indicates that the convection and conduction heat losses are more important than the radiation heat loss for this collector design which is reasonable since the glass cover should block most of the IR radiation. Despite the dominance of conduction and convection losses, there is still a clear correlation between heat losses and cloudiness which shows that heat losses due to irradiance are occurring and are measurable.

Furthermore Figure and Figure point out that the impact of wind velocity on the cooling energy, as well as the impact of cloudiness on the ambient temperature seems smaller than expected which leads us to conclude that the dominating factor is the convectional and conductional heat losses.

Figure 9 shows an night U-value of 4,2 W/m^2K which is close to the U-value measured during the day in previous papers.

Some PVT designs can go below ambient temperature. This is much less likely to happen in standard thermal panels. This is because the PV cells emit much more radiation than the selective surface of the thermal panels. Basically, a worse performance during the day by PVT collectors, leads to a better performance in cooling during the night. It is not reasonable to expect that a panel performs well in gaining heat during the day and, at the same time, also performs well at loosing heat during the night.

When speaking about heating, it is generally accepted that energy at ambient temperature has no value. For cooling, the same is generally true. The analyses of the measurements that have been made reveal that the C-PVT collector shows little potential for cooling applications. However, if the C-PVT design was made without a glass cover the results could potentially be very different for locations with many clear nights.

5. References

[1] Armenta-Déu, C., Donaire, T., Hernando, 2003. Thermal analysis of a prototype to determine radiative cooling thermal balance, Pergamon, Renewable Energy, Grupo de Energia Solar, Universidad Complutense, Spain

[2] Dobson, R.T., 2005. Thermal modelling of a night sky radiation cooling system, Journal of Energy in Southern Africa, Vol 16 No 2, Department of Mechanical Engineering, University of Stellenbosch

[3] Eicker, U., Dalibard, A., 2011. Photovoltaic-thermal collectors for night radiative cooling of buildings, Elsevier, Solar Energy, University of Applied Science Stuttgart, Germany

[4] Giovinazzo, C., Bonfiglio, L., Gomes, J., Karlsson, B., 2014. Ray Tracing Modelling of an Asymmetric Concentrating PVT, International Solar Energy Society, Ecole Polytechnique Universitaire de Montpellier, University of Gävle, France, Sweden

[5] Gomes, J., Diwan, L., Bernardo, R., Karlsson, B., 2013. Minimizing the Impact of Shading at Oblique Solar Angles in a Fully Enclosed Asymmetric Concentrating PVT Collector, Elsevier, Energy Procedia, University of Gävle, Instituto Superior Tecnico Lisboa, Lund University, Sweden, Portugal

[6] VDI-Wärmeatlas, 2013. Grundlagen der Wärmeübertragung, 11. edition, Springer-Verlag Berlin

Heidelberg, Germany

[7] World Weather: URL: http://www.worldweatheronline.com/Gavle-weather-history/Gavleborgs-Lan/SE.aspx, 09/28/15)

6. Appendix

Table 2: Results for all considered nights

Night [22:00 – 05:00]	E_{cold} [kWh]	$\dot{E}_{cold}$ [W]	T_{out} [°C]	T_{amb} [°C]	$T_{out} - T_{in}$ [°C]	$T_{coll} - T_{amb}$ [°C]	$Cloudiness$ [%]	v_{wind} [m/s]
05.09. - 06.09.	-1,08	-154,9	22,9	10,2	-0,88	13,2	5	2,1
06.09. - 07.09.	-0,71	-101,5	24,0	12,6	-0,57	11,7	39	1,2
09.09. - 10.09.	-0,72	-102,6	18,7	8,6	-0,58	10,5	41	1,8
10.09. - 11.09.	-0,83	-118,1	18,2	7,6	-0,67	10,9	4	0,4
09.10. - 10.10.	-2,0	-285,1	35,8	8,7	-1,85	28,1	89	1,8
10.10. - 11.10.	-0,61	-86,9	17,2	9,5	-0,57	7,9	53	2,4
11.10. - 12.10.	-0,84	-120,6	14,4	1,8	-0,79	12,9	48	1,5
12.10. - 13.10.	-0,53	-76,2	17,1	9,6	-0,49	7,7	95	1,6
14.10. - 15.10.	-0,62	-88,1	16,8	7,6	-0,57	9,4	92	3,3
17.10. - 18.10.	-0,75	-107,4	14,4	2,6	-0,70	12,1	7	1,5
19.10. - 20.10.	-0,56	-80,5	17,2	8,6	-0,52	8,9	100	1,0
21.10. - 22.10.	-0,62	-89,0	14,4	5,1	-0,58	9,8	97	4,5
22.10. - 23.10.	-0,78	-111,2	13,7	1,7	-0,62	12,4	33	3,1
23.10. - 24.10.	-0,67	-95,2	13,2	3,4	-0,55	10,1	100	5,8
24.10. - 25.10.	-0,52	-73,7	16,9	9,8	-0,43	7,3	99	5,8
28.10. - 29.10.	-0,44	-62,7	18, 6	12,7	-0,37	6,0	54	6,7
29.10. - 30.10.	-0,78	-112,1	12,9	1,9	-0,68	11,4	3	2,4
31.10. - 01.11.	-0,76	-108,0	12,7	-0,9	-0,64	13,9	63	1,8
01.11. - 02.11.	-0,44	-63,1	16,4	9,9	-0,37	6,7	94	4,8