

## Low energy cooling of buildings with radiative cooling using hybrid PVT collectors

Ursula Eicker, Antoine Dalibard, Simon Büttgenbach, Sebastian Fiedler, Jan Cremers

*University of Applied Sciences HFT Stuttgart, Germany, Schellingstraße 24, 70174 Stuttgart*

*Tel.: +49 711 8926 2831, Fax.: +49 711 8926 2698*

*Email: ursula.eicker@hft-stuttgart.de*

### ABSTRACT

A photovoltaic-thermal (PVT) cooling system concept has been developed, tested and implemented for a highly energy efficient building constructed for the first European Solar Decathlon competition in Madrid. Simulation and experimental studies of uncovered PVT collectors show very promising results for this kind of application which combine cooling during the night and photovoltaic electricity generation during the day. For the city of Madrid, where the competition will take place, a mean nightly cooling of 44 W/m<sup>2</sup> was calculated for the cooling period. The summer cooling energy production per square meter of PVT collector is 56 kWh/m<sup>2</sup>a, half of which is directly used for building cooling via PCM ceilings and radiant floors. The other 50% are used to take up rejected heat from a reversible chiller and thus improve its efficiency. In addition to the thermal cooling gain, an annual AC electricity production of the partially shaded PVT collectors of 141 kWh/m<sup>2</sup> can be obtained.

### 1. INTRODUCTION

Radiative cooling of buildings has attracted considerable research over the years, much of it focused on evaluating the magnitude of the resource and the variations in cooling potential among different locations. However, radiative cooling is still not applied in conventional buildings, partly because there has been relatively little research by engineers and architects dedicated to resolve problems of practical application. A further barrier to more widespread use of radiative night cooling systems is the low power density, which requires large roof surface areas and rather high mounting costs. On the other hand, many buildings are now completely covered with photovoltaic panels for solar electricity production. A low cost combination of photovoltaic modules with a thermal collector (PVT) could provide a very interesting and cost effective solution for radiative cooling applications.

Radiative cooling is based on the heat loss by long-wave radiation emission from a body towards another body of lower temperature, which plays the role of a heat sink. In the case of buildings the cooled body is the building surface and the heat sink is the sky. The sky temperature is lower, especially during night, than the temperatures of most of the objects upon earth. Sky temperature during summer nights can be <0°C, with clear summer night sky conditions even sky-temperatures of -10°C are possible (Cavelius, 2005).

Different applications have been investigated: moveable insulation, air based systems and open or closed water-based systems. The specific cooling power measured ranges from 20 to 80 W/m<sup>2</sup> (Cavelius, 2005).

One of the first applications of radiative cooling (end of the 60s) was the moveable insulation. The roof insulation is removed during the night in order to cool down the building through radiation towards the sky. The major drawback of such system is the motor-operated system to remove and replace the insulation panels (Santamouris, 2007).

Others early experiments with radiative cooling were carried out in Israel at the beginning of the 70s. They were based on radiative cooling of air flowing in a narrow channel. A similar

system combined with a solar chimney for winter was investigated by Brunold (1989). The maximum cooling output of the system under favourable environmental conditions was about  $17 \text{ W/m}^2$  (Santamouris, 2007).

Since water is (almost) incompressible and has a higher heat capacity, water-based systems can be better controlled with a low electrical energy input and a higher cooling output can be achieved. One of the first applications of a radiative cooling water-based system was carried out by Juchau (1981), who used a standard flat plate collector coupled with a storage tank to cool down water during the night. The cold water was used during the day to cool down the building through a concrete floor slab. This concept was further developed in Israel by Erell and Etzion (1992). By removing the cover, they obtained a net cooling power of  $81 \text{ W/m}^2$  for seven hours of operation each night over a three week period in the Summer of 1990.

Open water-based systems have been investigated more recently in Germany (Beck, 2006). This approach consists of letting the water flow on a tilted surface. Due to the high emissivity of water (typically 0.96) and since there is no additional thermal resistance between the water and the ambient, the expected cooling outputs are higher than for closed systems. Measurement data of the demonstration plant installed in Würzburg (Germany) show that a specific cooling power of  $120 \text{ W/m}^2$  can be achieved. With the cooperation of the University of Applied Sciences Stuttgart (UAS), a similar system has been planned for the Solar Decathlon 2007 by the Technical University of Darmstadt, winner of the competition.

Within the European Solar Decathlon competition taking place in Madrid in June 2010, the Stuttgart University of Applied Sciences (UAS) developed a completely renewable powered zero energy building with a useful floor area of  $56 \text{ m}^2$ . The building is equipped with a radiative cooling system using hybrid Photovoltaic and thermal (PVT) collectors.

## 2. DESIGN DECISION AND PVT CONSTRUCTION

Although open systems can achieve higher cooling output, their integration into the cooling distribution system presents some drawbacks compared to closed systems. Since the water is in direct contact with the atmosphere, a filter is necessary to prevent dust to enter the system. The system works at atmospheric pressure and therefore has to be decoupled from the distribution system (heat exchanger between radiant cooling loop and building cold distribution). Furthermore, water can evaporate to the ambient, which could result in significant water consumption. Simulation studies show that a nightly consumption of about  $0.1 \text{ kg/m}^2$  ( $3.5 \text{ kg/night}$  in total) can be expected for the Madrid climate conditions if an open system is chosen. For those reasons and in order to combine the cooling application with electricity generation, a closed water-based system with PVT collectors has been chosen.

Water based PVT collectors are normally used only during the day for electricity generation and thermal energy production. Depending on the application, the main objective is either the electricity production or the thermal output. In the first case, the fluid has to cool down the PV cells as much as possible in order to increase their efficiency. In the second case, one expects a certain outlet temperature of the fluid for a certain application (domestic hot water, thermal cooling etc.). The design of the PVT collector will depend mainly on the objective defined. Figure 2 shows the two main types of PVT collectors available on the market which are uncovered ( $n^{\circ}1$ ) and covered ( $n^{\circ}2$ )

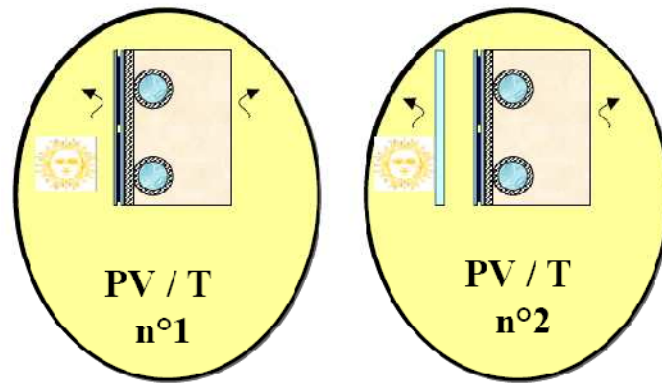


Figure 1: Uncovered and covered PVT collectors

To the knowledge of the authors, PVT collectors have not been used yet for night radiative cooling applications. This kind of application requires a special construction of the PVT module which allows a maximum heat loss by long-wave radiation emission from the PVT collector toward the sky. That is why the uncovered design has been chosen. Furthermore, the thermal contact between the absorber and the PV module has to be as good as possible. Within the last 10 years, the company PVTwins from the Netherlands ([www.pvtwins.nl](http://www.pvtwins.nl)) has put a lot effort on improving this thermal contact, developing their own technique for the absorber/PV module assembly. Their uncovered PVT collectors have been tested on the roof of Stuttgart UAS in order to estimate the cooling potential during the night.

### 3. EXPERIMENTAL SET-UP

The two tested collectors were provided from PVTwins for the measurements. The two collectors have been provided without the cover in order to maximize the heat transfer to the ambient/sky and one of them without the insulated box at the back. Figure 2 shows the collector tested and the experimental set-up on the roof.



Figure 2: PVT collector (PVTwins) and experimental set-up

A 270 liters tank with an electrical heater is used to store the cold water and heat the water during the day. Since the pump was too big to deliver the required flow rate (around 40 liter/hr m<sup>2</sup>), a mixing loop has been built. The surface temperature of the PV module is measured by 2 thermocouples: one at the fluid inlet and the other one at the outlet. The inlet and outlet fluid temperatures are measured with PT100 sensors. The scheme of the experimental set-up is shown in Figure 3.

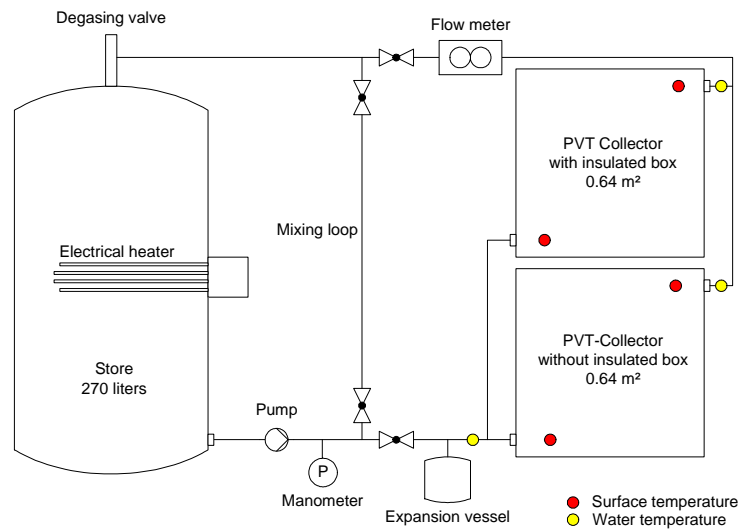


Figure 3: Scheme of the experimental set-up.

#### 4. THERMAL MODELLING OF THE PVT COLLECTOR

Modelling of standard thermal collectors has been already extensively detailed in the literature (Duffie and Beckmann, 2006). This model has been adapted for an uncovered flat plate collector used for radiative cooling application (Erell and Etzion, 2000).

Based on this approach, a model has been developed for an uncovered and non-insulated PVT collector used for night radiative cooling. Following the methodology developed by Duffie and Beckmann, first the overall heat loss coefficient of the collector (from the absorber to the ambient) has to be calculated. For an uncovered and non-insulated PVT collector, the thermal circuit diagram is shown in Figure 4:

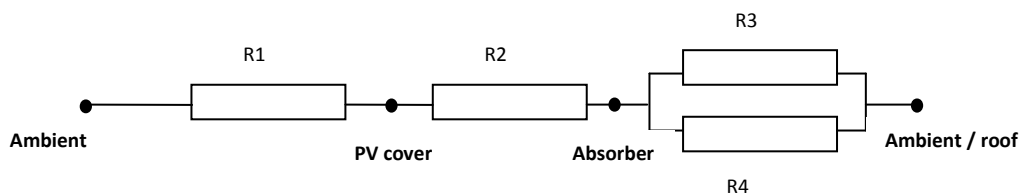


Figure 4: Thermal circuit diagram of the uncovered/non-insulated PVT collector

R1: Thermal resistance due to mixed convection (free + forced) from the PV cover to the ambient

R2: Thermal resistance due to conduction through the PV module + glue

R3: Thermal resistance due to radiation from the absorber towards the roof

R4: Thermal resistance due to free convection from the absorber (back side) to the ambient

The radiative heat exchange, which is the useful energy for cooling, is separated at first from the U-value calculations, i.e. the resistance from the PV cover to ambient only includes convective heat exchange. The overall thermal resistance calculation can be divided in two parts (back side and front side):

$$R_{\text{front}} = R_1 + R_2$$

$$R_{\text{back}} = \frac{R_3 R_4}{R_3 + R_4}$$

The overall heat transfer coefficient (U-value) is then determined from the thermal resistances:

$$U = \frac{1}{R_{\text{front}}} + \frac{1}{R_{\text{back}}}$$

The calculation of the thermal resistances R1, R3 and R4 are already detailed in the literature and therefore will not be discussed here. The calculation of the thermal resistance of the PV module requires construction details of a PV module. A typical configuration of laminated and encapsulated silicon solar cells with 3 mm glass and 0.1 mm Tedlar back surface has been used. The thermal resistance of the PV module plus glue (resistance R2) for a glue thickness of 0.1 mm and a thermal conductivity of 0.85 W/(mK) gives a resistance  $R_2 = 0.0079 \text{ m}^2\text{K/W}$ . The glue used is a mixed of epoxy resin and aluminium in order to enhance thermal conductivity. Next the overall heat transfer coefficient U can be determined. As the convective and especially the radiative heat transfer coefficients are temperature dependent, an iteration process has to be used.

Table 1: Main physical parameters of the PVT collector model

PVT module area (m <sup>2</sup> )	38
PV cover emissivity (-)	0.85
Absorber emissivity (-)	0.03
Roof emissivity (-)	0.1
Thickness of PV cover (Glazing+cells+glue) (m)	0.016
Thickness of absorber (m)	0.0002
Distance between pipes (m)	0.1
Pipe internal diameter (m)	0.015
Bond conductance of the pipe/absorber contact (W/(mK))	300
Thermal conductivity of the PV cover (Glazing+cells+glue) (W/(mK))	0.79
Thermal conductivity of the absorber (W/(mK))	220

The collector efficiency factor  $F'$  is calculated using the fin efficiency of the copper absorber and the tubes as for a standard flat plate collector. The conduction within the glass module with its low conductivity is negligible compared to the 0.2 mm copper absorber with a thermal conductivity of 350 W/mK. With the collector efficiency factor  $F'$  and the mass flow through the thermal collector the heat removal factor  $F_r$  can be calculated.

The difference with the Duffie and Beckmann approach for standard thermal collectors is that the short wave irradiation, which is in this case zero, is replaced by the net radiative heat loss  $R_{\text{net}}$ .

$$\dot{Q}_u = F_R A_C [R_{\text{net}} + U(t_{\text{in}} - t_a)]$$

$$R_{\text{net}} = h_r(t_{pv} - t_{sky})$$

$$h_r = \epsilon_{\text{glass}} \sigma (t_{pv}^2 + t_{sky}^2)(t_{pv} + t_{sky})$$

## 5. RESULTS AND MODEL VALIDATION

The model has been compared with measurement data for a period of 45 hours in October 2009 (

Figure 5).

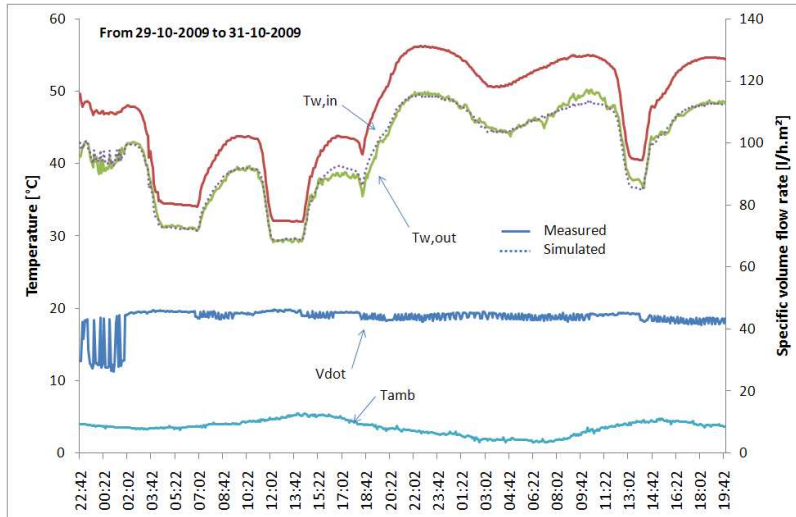


Figure 5: Measured and simulated of PVT collectors at the Stuttgart UAS.

The maximum deviation in outlet temperature between simulated and measured values is less than 2°C. The deviation in the global energy balance over the period is less than 1 %.

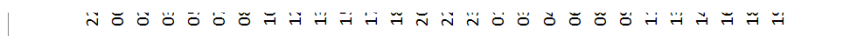


Figure 6 shows for the same period the output cooling power of the tested PVT module and the temperature difference between the inlet water temperature and the sky temperature. The correlation between those two values shows that the heat losses by long wave irradiation towards the sky are dominating.

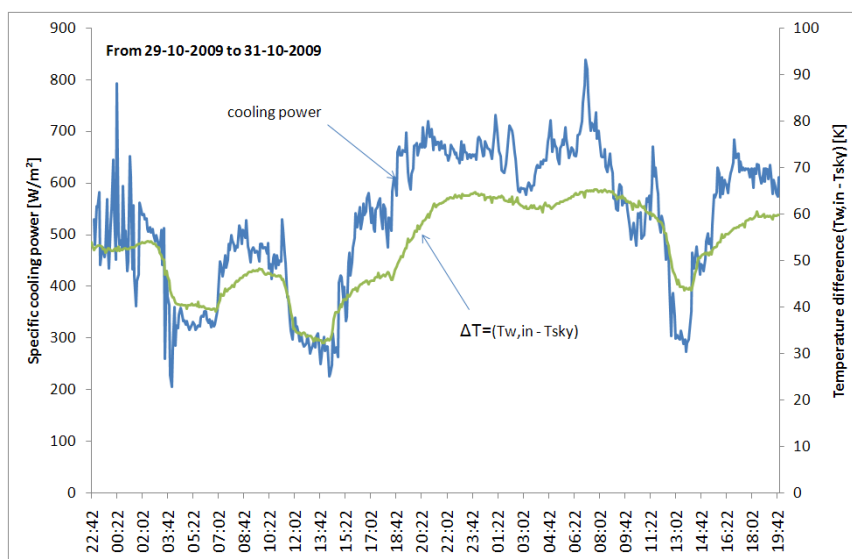


Figure 6: Cooling power output of the tested PVT collector (collector area 0.64 m<sup>2</sup>)

The model validation showed good results and the component model was then used for system simulations.

Measurements could only be done during autumn conditions with rather low ambient air temperatures. The collector inlet temperature was conditioned to give significant temperature differences between collector and calculated sky temperatures. The results show that below 30K temperature difference between PVT collector and sky, the specific cooling power is below 100 W/m<sup>2</sup> (see Figure 7).

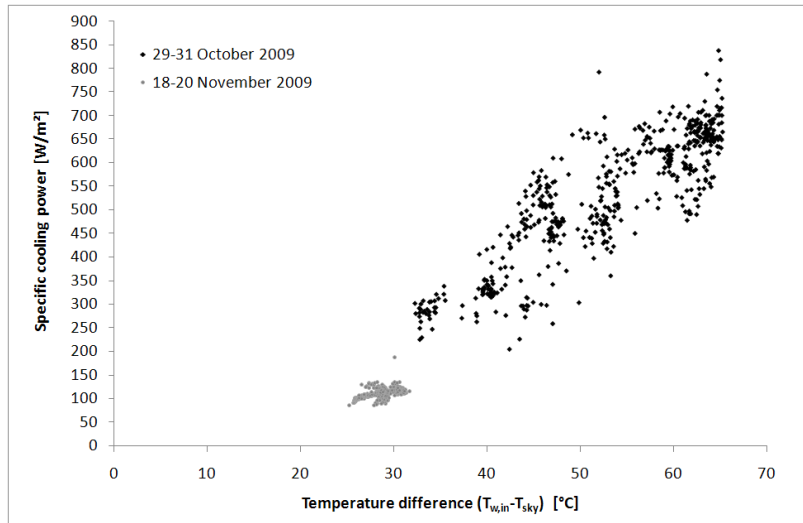


Figure 7: Specific cooling power as a function of measured PVT inlet temperature and calculated sky temperature

## 6. SYSTEM INTEGRATION AND SUMMER PERFORMANCE

The Solar Decathlon building has a night radiative cooling system consisting of 38 m<sup>2</sup> of PVT collectors located on the roof. The cold produced is used to remove heat loads from the building, which is mainly achieved by circulating cold water at night through a 18 m<sup>2</sup> phase change material ceiling to solidify the material, which has taken up heat during the day. In addition, the cooling energy is used for a 1.2 m<sup>3</sup> storage tank, which takes up heat rejected by a compression chiller during active cooling mode.

The PVT collectors are used during the night with the main priority to regenerate the PCM ceiling and then to cool down the 1.2 m<sup>3</sup> storage tank used as a heat sink for the compression chiller during the day. Only if the storage tank temperature is too high (above 45°C), the heat store is cooled down first.

Figure 8 shows the system integration of the radiative cooling system.

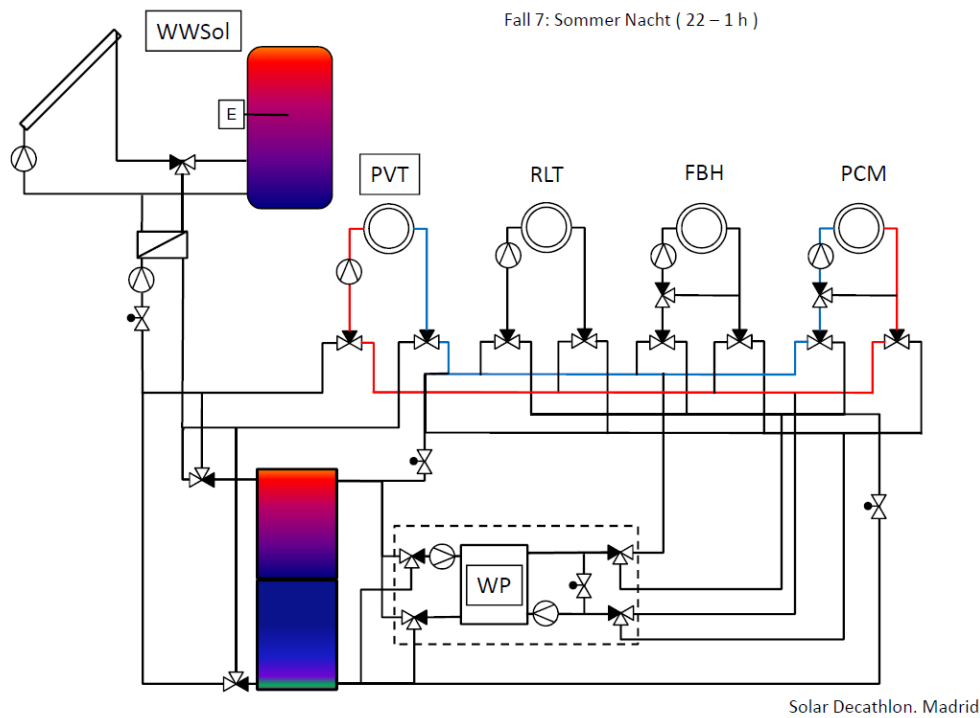


Figure 8: Radiative cooling for PCM ceiling regeneration

As the temperature difference between the cool PVT collectors and the warm heat store is usually higher than the temperature difference between PVT and PCM ceiling, the mean nightly cooling power is higher for the heat store re-cooling. For a given electrical power of the circulation pump between PVT and building, this means higher electrical COP's for the heat store re-cooling. For the Madrid/Spain climate the average performance results are given in Table 2.

Table 2: Radiative cooling power with PVT collectors

Mean cooling power (W/m <sup>2</sup> )	Mean cooling power when connected to PCM ceiling (W/m <sup>2</sup> )	Mean cooling power when connected to heat store (W/m <sup>2</sup> )
43.8	31.0	46.4
Electrical COP (-)	Electrical COP when connected to PCM ceiling (-)	Electrical COP when connected to heat store (-)
32.5	13.6	75.4

The total cooling energy produced by the PVT collectors is 2136 kWh, which corresponds to 60 kWh/m<sup>2</sup> energy production.

The specific cooling energy delivered from the PVT collectors to the PCM ceilings during summer is 620 kWh, which corresponds to 11 kWh/m<sup>2</sup>. A further 1516 kWh are supplied to

the heat store, of which 410 kWh are directly used to cool a 30 m<sup>2</sup> radiant floor. The remaining 1106 kWh are used for heat rejection of the chiller.

The PCM ceiling covers 30% of the total building cooling energy demand of 40 kWh/m<sup>2</sup> a. Free cooling using water below 19°C temperature from the heat store supplies 7.3 kWh/m<sup>2</sup>a, i.e. a further 20% of the building cooling demand. Another 30% of the cooling demand is supplied by a reversible heat pump, and the remaining 20% by indirect evaporative cooling of the ventilation supply air. Due to the re-cooling of the heat store by the PVT collectors, the reversible heat pump reaches a very good average COP of 4.0.

## 5. CONCLUSIONS

Within the competition of the Solar Decathlon Europe, the Stuttgart UAS developed a new concept of radiative cooling using PVT collectors. A market available PVT module has been tested in the laboratory. A simulation model has been developed and compared with measurement data. The results show good agreement between simulated and measurement values. The model has been used for simulation of the radiative cooling system of a highly efficient and even energy positive single family house. The mean PVT cooling power for the climatic conditions in Madrid/Spain were 44 W/m<sup>2</sup> during night hours. The total cooling energy production during summer was 56 kWh/m<sup>2</sup>. About 30% of this energy can be used to discharge phase change materials in the building ceiling and keep the room temperatures in a comfortable range. Another 20% of the cooling energy is used for direct cooling of a radiant floor. The remaining cooling energy is used very efficiently to re-cool a heat store which is used for heat rejection of a reversible heat pump.

## REFERENCES

Beck, A.; Büttner, D.: Kühlkreislauf mit passiver Kälteerzeugung durch Strahlungskühlung. In: Veröffentlichungen der Hochschule für Technik Stuttgart, Band 80 – Bauphysikertreffen 2006, p. 91

Cavelius, Ralf, Isaksson, Charlotta, Perednis, Eugenijus, Read, Graham E. F. “Passive cooling technologies”, Austrian Energy Agency, 125 pages, 2005.

Duffie and Beckmann, “Solar engineering of thermal processes”, Wiley, 3<sup>rd</sup> Edition, 2006.

Erell, E., Etzion, Y. “A radiative cooling system using water a heat exchange medium”, Architectural Science Review, vol. 35, p.39-49, 1992.

Erell, E., Etzion, Y. “Radiative cooling of buildings with flat plate collectors”, Building and Environment, Vol. 35, p. 297-305, 2000.

Lee, B., Liu, J. Z. , Sun, B., Shen, C. Y., Dai, G. C. “Thermally conductive and electrically insulating EVA composite encapsulants for solar PV cells”, eXPRESS Polymer Letters, Vol. 2, N° 5, p.357-363, 2008.

Santamouris, Mat “Advances in passive cooling”, Buildings, Chapter 7 “Radiative cooling”, Energy and Solar Technology Series, ISBN 1844072630, 2007.