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Influence of the environmental parameters on nocturnal radiative cooling capacity of solar collectors

Thibault Q. Péan*, Luca Gennari, Ongun B. Kazanci,
Eleftherios Bourdakis, Bjarne W. Olesen

International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark.

*thipe@byg.dtu.dk

Abstract

The weather dependency of nocturnal radiative cooling technology with solar collectors is investigated in this study. Two types of solar panels are investigated: unglazed collector and photovoltaic/thermal (PV/T). A computational model of both panels, validated by comparison with previous experimental results, enables to realize a parametric study on the cooling output, with variations on the following parameters: relative humidity, ambient temperature, cloud cover, cloud base height, and wind speed.

The results show that nocturnal radiative cooling highly depends on weather conditions. The cooling output is affected the most by the air temperature, which impacts both the radiative and convective heat losses. It was observed in this case that the cooling energy produced in one night is decreased by 75% when the temperature increases by 9°C; while the opposite change (temperature drop of 9°C) results in a +65% increase in the cooling output. Cloudiness, wind speed and relative humidity also affect the cooling output significantly. Unglazed collectors proved to be slightly more efficient for cooling applications than PV/Ts.

Keywords - Nocturnal radiative cooling; photovoltaic/thermal panels; unglazed collector; parametric analysis; computational simulation.

1. Introduction

Nocturnal radiative cooling has become a subject of research over the last decades, given its potential as a renewable source of cooling [1,2,3]. This technology simply consists in exploiting the radiation heat transfer to the cold nocturnal sky in order to cool a medium such as water. It is particularly adapted to solar thermal panels which are already facing the sky and could be used also at night for cooling purposes.

A literature review on the topic is presented by Péan et al. [4]. Two types of panels, unglazed collectors as well as photovoltaic/thermal (PV/T) panels were previously studied with regards to nocturnal radiative cooling in Kgs. Lyngby, Denmark [4]. That research focused on evaluating experimentally the potential of these two systems under the Danish climate. The present study extends the evaluation to different weather conditions, by developing a computational model of unglazed solar collectors and PV/T panels. The model is validated by comparison with the experimental results reported by Péan et al. [4] and then used to study the influence of different environmental parameters on the cooling performance. It eventually leads to the evaluation of the potential of this technology under different climates.

2. Methods

2.1. Description of the TRNSYS model

Figure 1. The studied unglazed solar collector (left), and the three PV/T panels (right). A schematic drawing of the experimental setup can be found in [4].

As in the experimental study [4], two different systems were investigated: one unglazed collector of 2.4 m^2 (Figure 1, left), and three PV/T panels of 1.3 m^2 each (mounted in series, Figure 1, right). They are modelled with the commercial software TRNSYS. The unglazed collector is modelled with Type559, and the PV/T panels with Type560. Their input parameters are reported in Table 1.

Table 1. Input parameters for PV/T panels and unglazed collector models.

Parameter PV/T	**Unit**	**Value**
Collector length	m	1.315
Collector width	m	0.996
Absorber plate thickness	m	0.001
Number of tubes	-	15
Thermal conductivity of the absorber	W/mK	380
Tube diameter	m	0.036
Bond thickness	m	0.001
Bond thermal conductivity	W/mK	380
Bond width	m	0.01
Resistance of back material	m^2K/W	2.8
Resistance of substrate material	m^2K/W	0.001

Parameter PV/T	**Unit**	**Value**
Fluid specific heat	kJ/kg.K	4.190
Reflectance	-	0.15
Emissivity	-	0.98
Collector slope	°	45
Fluid heat transfer coefficient	-	350

Parameter unglazed collector		
Collector length	m	2
Collector width	m	1.2
Fluid specific heat	kJ/kg.K	4.190
Emissivity of the absorber plate	-	0.96
Plate absorptance	-	0.95

The weather conditions (air temperature, wind velocity and atmospheric pressure) are provided as input to the panels. In addition to those, a radiation processor (Type16) calculates the total horizontal and diffuse radiation as well as the incidence angle on the sloped collectors. The effective sky temperature T_{sky} (K) is one of the major parameters influencing the radiative part of the heat transfer. As it is a fictive parameter, not directly measurable (it is the equivalent temperature of the sky considered as a black body), it is calculated based on the weather conditions, according to the following formulae [5,6]:

$$T_{sky} = \varepsilon_{sky}^{1/4} \cdot T_a \quad (1)$$

$$\varepsilon_{sky} = \varepsilon_0 + (1 - \varepsilon_0) \cdot \varepsilon_c \cdot n \cdot e^{-Z_c/Z_*} \quad (2)$$

$$\varepsilon_0 = 0{,}71 + 0{,}0056 \cdot T_{dp} + 0{,}000073 \cdot T_{dp}^2 \quad (3)$$

where

ε_{sky}	[-]	Emissivity of the sky
T_a	[K]	Ambient air temperature
ε_0	[-]	Emissivity of the sky in clear sky conditions
Z_c	[km]	Cloud base height
Z_*	[km]	Reference value fixed to 8.2 km
ε_c	[-]	Hemispherical cloud emissivity • $\varepsilon_c \approx 1$ for $Z_c < 4$ • $\varepsilon_c = 0.74 - 0.084 \cdot (Z_c - 4)$ for $4 < Z_c < 11\ km$ • $\varepsilon_c = 0.15$ for $Z_c > 11\ km$
n	[-]	Fractional cloud amount of the sky covered by opaque clouds, $0 \le n \le 1$

In the case of the unglazed collector, one important parameter is the collector efficiency factor. This parameter has been calculated following the method defined by Duffie and Beckman [5].

2.2. Validation of the model

In order to validate the model, simulations are carried out with the same conditions as recorded during the experiment that took place in Kgs. Lyngby, Denmark in August 2014 [4]. Therefore, the environmental conditions recorded by a weather station, as well as the supply temperature of the water recorded at the inlet are provided as input to the software. The flow rate was fixed to 75 l/h for the unglazed collector, 121 l/h for the 3 PV/T panels mounted in series, which corresponds to 30 l/h.m^2 of panel in both cases, identical to the experimental conditions.

Using the model described in section 2.1, simulations are carried out for the nights between 13/08/2014 and 25/08/2014[1] (12 nights in total), from 19:00 to 07:00. The obtained cooling power curves are used to calculate the cooling energy per night [4] which is then compared with the values from the experiment. The comparison results are presented in Figure 2. It can be observed that the simulation and the experimental results follow the same trend, with however an average error of 13% for the unglazed collector and 21% for the PV/Ts. In general, it can be seen that the TRNSYS model underestimates the cooling energy produced, especially in the PV/T case.

[1] The date mentioned for one night is the date at which the night starts.

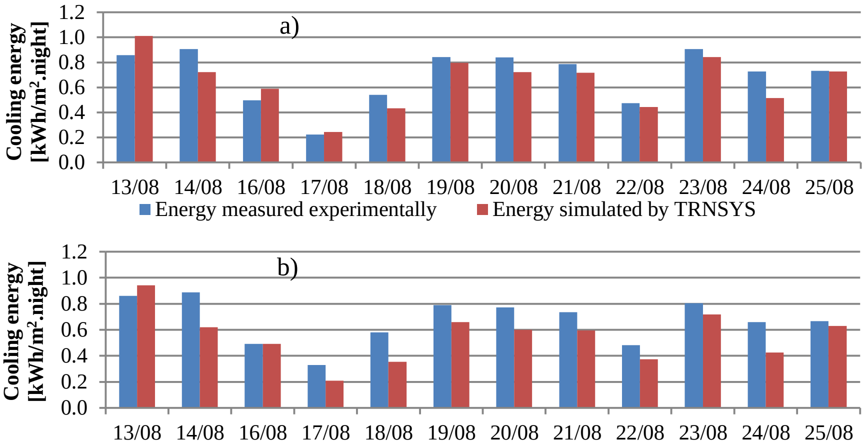

Figure 2. Comparison between experimental and simulated results.
a) Unglazed collector. b) PV/T.

The observed range of error should not be neglected, but several considerations enable to consider the model results usable for further analysis. The first consideration consists in taking into account the effect of rain. By highlighting the rainy days on the relative error graph, (Figure 3), it appears that rain can affect the results in a negative way, increasing the error. In fact, it was observed that during the days with rain, the average relative errors are 28.2% and 14.2% for the PV/T and unglazed panels respectively, while this error drops down to respectively 13% and 12% during the days without rain (Table 2). This difference is significant in the PV/T case. It is assumed that the presence of rainwater on the upper surface of the panel could influence the heat transfer, mainly through additional evaporative cooling, which is not accounted for in the TRNSYS model. Rainwater could also have affected the physical measurements taking place outside, making the results of rainy days less reliable.

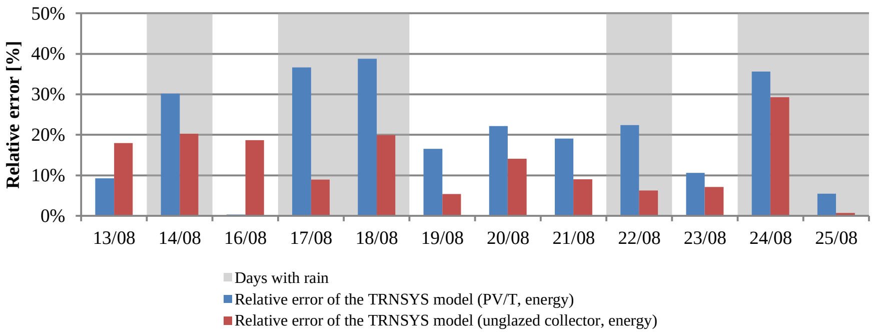

Figure 3. Relative error in relation with rain.

Table 2. Comparison of relative errors for the days with and without rain.

	Energy		Power	
	PV/T	Unglazed collector	PV/T	Unglazed collector
Average error - Days with rain (6 days)	28.2%	14.2%	24.9%	11.4%
Average error - Days without rain (6 days)	13.0%	12.0%	12.9%	11.5%

The second consideration concerns the input data about the cloud cover. Measuring cloudiness requires complex and expensive sensors, and it was therefore not realized during the measurements. The cloud cover data used in the simulations was retrieved from a weather station located 10 km away from the experiment location (Vedbæk). Furthermore, this data were provided only hourly while the time step of the simulations is 1 minute. This could explain part of the relative error observed between simulations and experimental measurements; therefore the model is considered valid and utilized further on for the parametric analysis.

2.3. Parametric analysis on the effects of environmental parameters

A reference case is chosen for the parametric study. The nights ranging from 01/08 until 04/08 are extracted from the reference weather file of Copenhagen from International Weather for Energy Calculation (IWEC) [7]. This particular period is chosen because it represents a case worth investigating with regards to nocturnal radiative cooling: mostly sunny with low cloudiness, and relatively warm temperatures. The warm weather and the high solar irradiation means there could be a need for cooling during this period (high solar gains), while the clear sky should favor the heat exchange by radiation and therefore the production of cold water.

The four considered nights are simulated in the previously described TRNSYS model, with a time-step of one minute, and a water supply temperature of 25°C. The cooling energy produced per night is calculated from 19:00 to 7:00. This constitutes the reference case, reported in section 3.1. From this case, one parameter is chosen at a time, and varied within its potential range (Table 3). The influence of these parameters on the cooling output is then reported in sections 3.2 to 3.6. The effective sky temperature is not directly studied as a varying parameter, because several of the other parameters directly affect its value (relative humidity, air temperature, cloud cover and base height).

Table 3. Parameters varied for the parametric study and their respective ranges.

Parameter	**Range observed for the parametric study**
Relative Humidity	20% to 100% by steps of 20%
Air temperature	The reference temperature curve is shifted by -9°C, -6°C, -3°C, +3°C, +6°C and +9°C
Cloud cover	0 to 100% by steps of 20%
Cloud base height	0.5 km, 1 km, 5 km, 10 km, 20 km
Wind speed	0 to 15 m/s by steps of 5 m/s

3. Results of the parametric analysis

3.1. Results of the reference case

The results in terms of average cooling power and cooling energy are presented in Table 4, for the reference case described in 2.3:

Table 4. Results of the reference case.

	Unglazed collector		PV/T	
	Average power	Cooling energy	Average power	Cooling energy
	W/m^2	kWh/m^2.night	W/m^2	kWh/m^2.night
01/08/1999	140.28	1.68	119.54	1.43
02/08/1999	140.31	1.68	119.82	1.44
03/08/1999	134.06	1.61	113.81	1.37
04/08/1999	134.20	1.61	115.46	1.39

As expected from the favorable conditions and high supply water temperature, the average power is relatively high during these four nights, compared to the values encountered in the literature [1,2,3,4], where the reported cooling capacity rarely exceeds 100 W/m^2. In this range of cooling capacity, it appears that unglazed collectors are slightly more efficient than PV/Ts, while in a lower cooling capacity range (20 to 75 W/m^2), no noticeable difference was observed [4]. Heat losses through radiation accounted for an average of 88% of the total heat losses in the PV/T case (convection heat losses constituted the rest).

3.2. Relative Humidity

The results of the parametric study on relative humidity (RH) are presented in Figure 4. Changes in relative humidity affect the dew point temperature, which directly influences the effective sky temperature, as seen in (1), (2) and (3). A low relative humidity (RH=20%) enables to increase the cooling energy by 45% and 48% for unglazed collector and PV/T respectively, compared to the case with highest relative humidity (RH=100%).

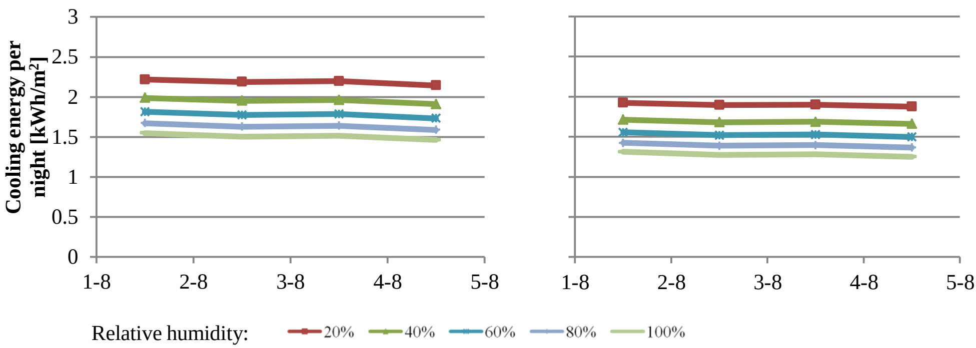

Figure 4. Parametric analysis results for unglazed collector (left), and PV/T (right).

3.3. Air temperature

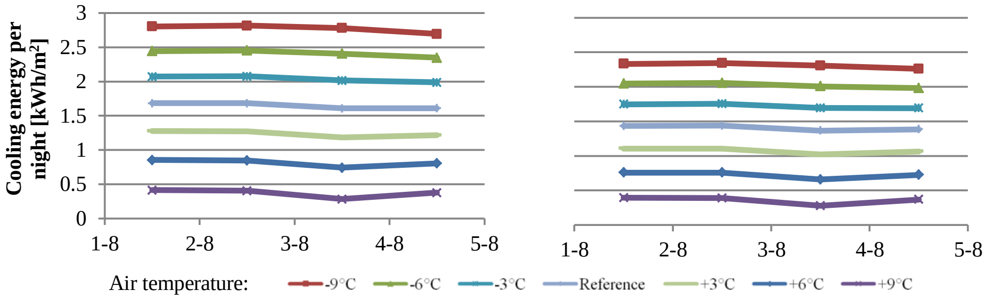

Figure 5. Parametric analysis results for unglazed collector (left), and PV/T (right).

The results of the parametric study on air temperature are presented in Figure 5. It can be seen that the ambient air temperature has the biggest impact on the cooling performance compared to the other parameters studied in the present research. This is due to its influence on both the radiative (through the sky temperature) and convective parts of the heat transfer. Compared to the reference case for the unglazed collector, the variation in cooling energy is +69% when the temperature is lowered by 9°C, and -78% when the temperature is increased by 9°C. These values are comparable for the PV/T case, with +64% and -75% respectively. The large span of cooling energy observed in these simulations (0.4 to 2.8 kWh/m^2) suggests that the cooling performance is highly dependent on the air temperature. Furthermore, it should be added that in the case where the temperature is the highest (+9°C above the reference case), the convective heat transfer produces the unwanted effect of heating (at a rate of 9 W/m^2) instead of cooling, which explains the lower performance. This counter-effect was notably reported by Eicker and Dalibard [8] under the climate of Madrid, with convective heat gains of 13.5 W/m^2.

3.4. Cloud cover

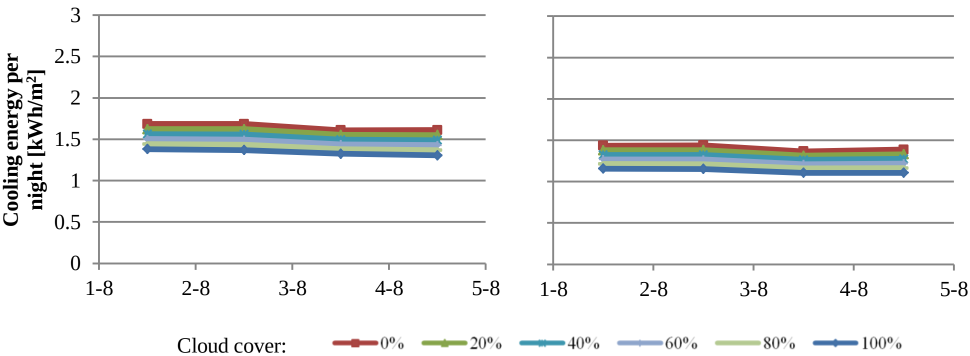

Figure 6. Parametric analysis results for unglazed collector (left), and PV/T (right).

The results of the parametric study on the cloud cover are presented in Figure 6. For this set of simulations, the cloud base height has been set to 5 km, otherwise the cloud layer was situated too high in altitude to observe any impact of the cloud cover changes on the cooling performance. It is observed that in this case, the clear sky induces an increase in cooling energy of respectively 22% and 24% for the unglazed collector and the PV/T, compared to a completely cloudy sky. It is expected that these percentages would vary considerably with the altitude of the cloud cover (see also section 3.5).

3.5. Cloud base height

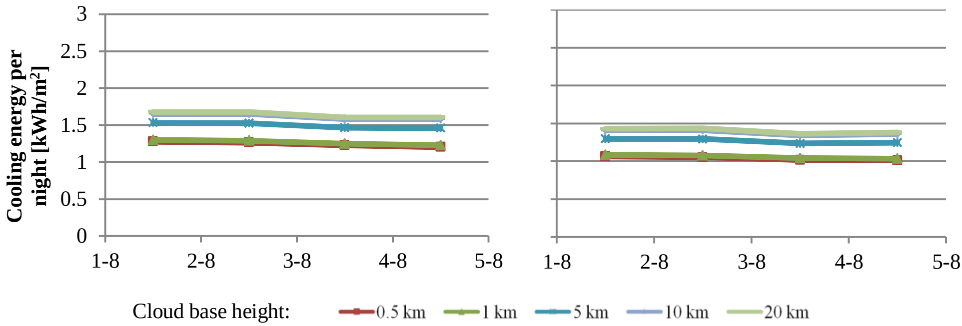

Figure 7. Parametric analysis results for unglazed collector (left), and PV/T (right).

The results of the parametric study on the cloud base height are presented in Figure 7. For this set of simulations, the cloud cover has been set to 50%; otherwise the mostly clear sky of the considered period would not allow distinguishing the impact of the cloud base height on the cooling performance. The results show that a lower cloud cover reduces the production of cooling. However, it appears that the largest impact occurs when the clouds are between 1 and 10 km high; outside this range the cooling energy changes with minor amplitude.

3.6. Wind speed

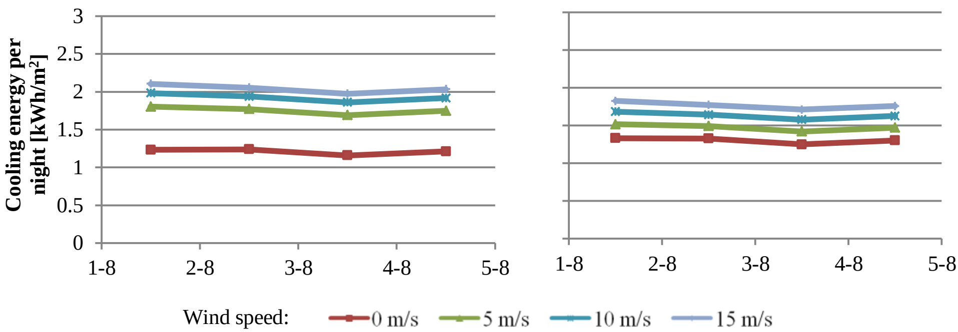

Figure 8. Parametric analysis results for unglazed collector (left), and PV/T (right).

The results of the parametric study on the wind speed are presented in Figure 8. Even though the wind speed only affects the convective part of the heat losses, the variations of this parameter have a significant impact on the overall cooling performance. The case with highest wind speed (15 m/s) presents a cooling energy increased by 69% for the unglazed collector and by 36% for the PV/Ts, compared to the case with no wind.

4. Discussion

As in every simulation work, the accuracy of the considered model can be discussed. The numerous input parameters necessary to simulate a panel are difficult to encounter when modeling an existing product, therefore some of them need to be assumed with the most realistic values. Furthermore, the simulation models of solar thermal panels are optimized for the daytime operation and calculation of heat gains, in order to assess the heating production. The nocturnal cooling focuses on the calculation of heat losses rather than heat gains, it is therefore probable that this affects the results. The authors have tried to minimize the impact of these errors by validating the model with experimental results.

Another bias in the results could stem from the independent variation of weather parameters. Climate consists of a whole set of interdependent parameters. Extracting one of them to realize separate variations is not a realistic approach. However, this study focuses on the relative impact of each parameter, and therefore the realism of the absolute values is not the prime interest.

The water supply temperature has not been varied in this study, it was fixed at 25°C. This choice is explained by the possibility of coupling a nocturnal radiator to a high temperature cooling system, whose output would be in this temperature range. However, it is clear that the water supply temperature affects the cooling output, as suggested for example by the comparison of the reference case with the experimental studies [4].

5. Conclusion

This study shows that nocturnal radiative cooling depends highly on the weather conditions. The cooling output can fluctuate significantly, as for other types of renewable energies such as solar or wind power. This could cause issues if one is to integrate nocturnal radiative cooling in the global energy mix. Increasing the share of renewable energies, whose production constantly fluctuates depending on the weather conditions, make the management of the global energy grid more complicated. However, if the sources of renewable energy each depend on different weather parameters, it becomes easier to ensure a minimum production of energy, for any kind of weather conditions encountered. This is one reason why this research on the weather-dependency of such technology is relevant.

The results show that the production of radiative cooling at night mostly depends on the sky temperature, which depends itself on several parameters. The air temperature has the biggest impact on the performance since it influences both the radiative and convective cooling: a +9°C increase in temperature causes the cooling output to drop by approximately 75%, and a -9°C decrease in temperature causes the cooling output to increase by 65%. Clouds, relative humidity and wind speed also affect the cooling performance considerably.

The dependency of nocturnal radiative cooling on the sky clearness does not necessarily constitute a disadvantage. Indeed, clear sky conditions induce both higher solar gains during daytime (which means a higher need for cooling), and higher potential for cooling during nighttime. Provided that the clear-sky conditions are stable over several days and nights, it thus implies contemporaneity between the cooling demand and supply, which makes this technology particularly promising.

The present study shows that unglazed collectors are slightly more efficient for cooling operation than PV/Ts. The difference is particularly more pronounced when the cooling power reaches higher values (mostly above 100 W/m^2). The main reason is the composition of the panels: PV/Ts are covered by a glazing pane that reduces the heat losses (which is optimized for heating purpose), while the unglazed collectors inherently lose more heat (which is not optimal for heating purpose but becomes an advantage for cooling applications).

According to this study, the climates more favorable to the implementation of nocturnal radiative cooling would present the following criteria for a significant amount of the year: lower temperatures at night, clear skies, relatively dry weather and possibly windy. Arid climates notably present these criteria and could be studied for further research.

Acknowledgments

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