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Simulation Study of Discharging PCM Ceiling Panels through Night-time Radiative Cooling

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ABSTRACT

A simulation study was conducted to examine the possibility of using PhotoVoltaic/Thermal (PV/T) panels and unglazed solar collectors for producing cold water through night-time radiative cooling. The cold water was used as the medium for cooling an office in three different cities (Copenhagen, Denmark, Milan, Italy and Athens, Greece) during the cooling period (1st of May – 30th of September). For cooling the office, radiant ceiling panels including Phase Change Material (PCM) were used. In Athens and Milan the operative temperature was within the range of Category III of EN 15251 (23 – 26°C, 73.4 – 78.8 °F) for 81% and 82% of the occupancy period respectively, while in Copenhagen it was within the same range for 63%. Night-time radiative cooling provided for Copenhagen 22%, for Milan 10% and for Athens 4% of the cooling energy required for discharging the PCM. The total electricity produced in Copenhagen for the simulated period was 94.4 kWh/m² (29900 Btu/ft²), while for Milan and Athens it was 96.7 kWh/m² (30700 Btu/ft²) and 111.7 kWh/m² (35400 Btu/ft²)respectively. It was concluded that night-time radiative cooling can be a satisfying solution for providing space cooling to office buildings in northern climates. The performance of the installations could be improved by implementing a solar shading system and a more precise control strategy.

INTRODUCTION

The global energy use has been increasing drastically in the past decades, mainly due to the population growth and the industrial and technological progress. In order to address this issue, the European Union (EU) launched several directives to decrease energy use, increase energy efficiency and increase the use of renewable energy sources (EP, 2009, 2010). The aim is that by 2020 all new buildings constructed in the EU must be nearly zero-energy buildings. A solution that could contribute achieving this goal is coupling photovoltaic panels for the production of electricity and phase change material (PCM) for the reduction of peak cooling demand.

PCMs are organic (e.g. paraffin) or inorganic (e.g. salts) substances which absorb latent heat when they melt and release it when they solidify. During the melting and solidifying process their thermal capacity increases considerably. The advantages of PCMs compared to conventional construction materials are the reduction of peak cooling load, the increase of the thermal inertia of the building, the shift of portion of the cooling demand to night-time where electricity prices are lower in several countries, the reduction of the room air temperature fluctuation and the reduction of the size of the heating and cooling system (Koschenz & Lehmann, 2004; Cabeza et al., 2007; Pavlov,

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2014; Grossule, 2015).

One passive method that could be utilized for discharging the PCM is the night-time radiative cooling. During night-time the solar collectors have a higher temperauter than the sky; therefore they release heat towards the sky in form of radiation. There are several ways with which night-time radiative cooling can be exploited (Grossule, 2015); in this study a closed water based system will be simulated. The main advantages of such a system are the reduction of energy use, since the only electrical energy required is that for the operation of a recirculation water pump and a higher utilization factor for solar thermal panels since they are exploited also during the night. Cooling demand and cold water production through night-time radiative cooling are in phase since clear sky occurs more often during summer and it can be coupled with thermal storage materials such as PCM (Eicker & Dalibard, 2011; Hosseinzadeh & Taherian, 2012; Meir, Rekstad, & Løvvik, 2002).

The purpose of this simulation study was to examine the coupling of suspended ceiling panels including PCM for conditioning an office room with solar collectors, exploited for discharging the PCM passively through night-time radiative cooling. The combination of these two technologies was tested in three different locations, namely Copenhagen (Denmark), Milan (Italy) and Athens (Greece). The system was evaluated in terms of the resulting indoor thermal conditions, the electricity production and the cooling output of the PV/T panels.

METHOD

A software based model was created to simulate a two persons' office room in three different locations, namely Copenhagen (CPH), Milan (MIL) and Athens (ATH). The floor area was 22.7 m^2, 244.3 ft^2 (5.4 m X 4.2 m, 17.7 ft X 13.8 ft) while the height was 3 m, 9.8 ft. At 2.5 m (8.2 ft) above the floor the radiant system with the PCM was installed as a suspended ceiling. The plenum that was formed between the suspended ceiling and the office's roof was used to supply fresh air inside the room. A vertical section of the office room is shown in Figure 1. The external wall of the office faced south and the office was assumed to be in an intermediate floor of an office building. Therefore, three walls, the roof and the floor were adjacent to office rooms with identical thermal conditions and only the south wall was exposed to ambient weather conditions. The U-value of the external wall was 0.3 W/(m^{2}K), 0.1 Btu/ft^2·h·°F while the internal surfaces had a U-value of 4.9 W/(m^{2}K), 0.9 Btu/ft^2·h·°F. On the external wall there was a 3 m^2, 32.3 ft^2 window with a U-value of 1.4 W/(m^{2}K), 0.2 Btu/ft^2·h·°F and a g-value of 0.59. The heat gains of the office consisted of two occupants at sedentary activity level (1.2 Met), the corresponding office equipment and the ceiling lighting which in total was 540 W, 1843 Btu/h (23.8 W/m^2, 7.5 Btu/h·ft^2). The heat gains were activated during typical office hours, namely from 9:00 to 17:00.

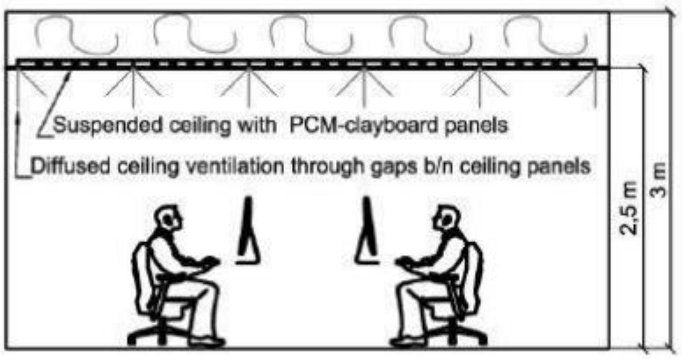

Figure 1. Vertical section of the simulated office room (Pavlov, 2014)

The external diameter of the pipes supplying cold water to the suspended ceiling was 8 mm, 0.026 ft, the thickness 1 mm, 0.003 ft and the pipe spacing 85 mm, 0.279 ft, while the water flow rate was 150 kg/h, 331 lb/h. The ventilation air flow rate was set to 30 L/s, 63.6 ft^3/min (1.9 ACH), sized according to EN 15251 (DS/EN 2007) for providing fresh air and removing pollutants. The air supply temperature was 18.5°C, 65.3°F and the ventilation was operated from 9:00 until 17:00 every day.

For providing electricity, hot water and cold water for the radiant system, three PhotoVoltaic/Thermal (PV/T) panels and an unglazed solar thermal collector were used. The emissivity of the absorber plate of the unglazed solar collector was 0.91 while for the PV/Ts was 0.89. The plate absorptance of the collectors was 0.95. The PV/T panels had 15 water tubes with an inner diameter of 18 mm (0.06 ft) and a thickness of 1 mm (0.003 ft). The panels were facing south with a tilt angle of 45°. The total surface of the PV/Ts was 3.9 m^2, 42 ft^2 and for the unglazed collector 2.4 m^2, 25.8 ft^2. The water flow rate in the solar panels was 100 kg/h, 220 lb/h and was split in 62 kg/h, 136 lb/h for the PV/Ts and 38 kg/h, 84 lb/h for the unglazed collector in order to ensure the same flow per m^2 for the two types of solar collectors. Two tanks were used to store hot water (HWT) and cold water (CWT). Between the solar collectors and the tanks a plate heat exchanger was installed. The direction of the water after the heat exchanger toward the HWT or the CWT was determined automatically based on the two following conditions:

- If $T_{PV/T} - T_{HWT} > 3\ K$ then water directed towards HWT (1)
- If $T_{CWT} - T_{PV/T} > 3\ K$ then water directed towards CWT (2)

where $T_{(PV/T)}$ is the water temperature exiting the PV/T panels, T_{HWT} is the temperature in the middle of the HWT and T_{CWT} is the temperature in the middle of the CWT. If neither of the two conditions was met, then the pump between the heat exchanger and the tanks was switched off. The CWT had two internal spiral heat exchangers. The upper one was connected to the heat exchanger, while the lower one was connected to a chiller (air-to-water heat pump) as shown in Figure 2. The chiller was used as an auxiliary system for providing cold water when the production from night-time radiative cooling was not sufficient. The heat pump had a seasonal COP of 5.4 (18.4 EER). The chiller could be activated from 00:00 until 09:00 provided that the temperature in the middle of the CWT was above 18°C, 64.4°F. The temperature of the water leaving the chiller was 12°C, 53.6°F. The water from the lower part of the CWT was circulated to the PCM panels and from there it was returned to the top of the CWT. The water flow rate was 150 kg/h and the circulation of the water was started at 20:00 and continued until 09:00, provided that the following conditions were met:

- The average lower surface temperature of the PCM panels was above 21°C, 69.8°F
- The operative temperature of the room was above 21°C, 69.8°F
- The temperature of the water in the middle of the CWT was below 20°C, 68°F

The hot water was not utilized, e.g. through a tapping schedule and the tank was used only to store hot water in order to reduce the surface temperature of the PV/T panels. In this way the efficiency of the PV/T panels in terms of electricity production would be increased.

The simulation period for all cases was from the 1st of May until the 30th of September which is considered the cooling period in Denmark. For the simulations, the International Weather for Energy Calculations (IWEC) files for Copenhagen, Milan and Athens were used. In Figure 2 the schematic drawing of the system is shown.

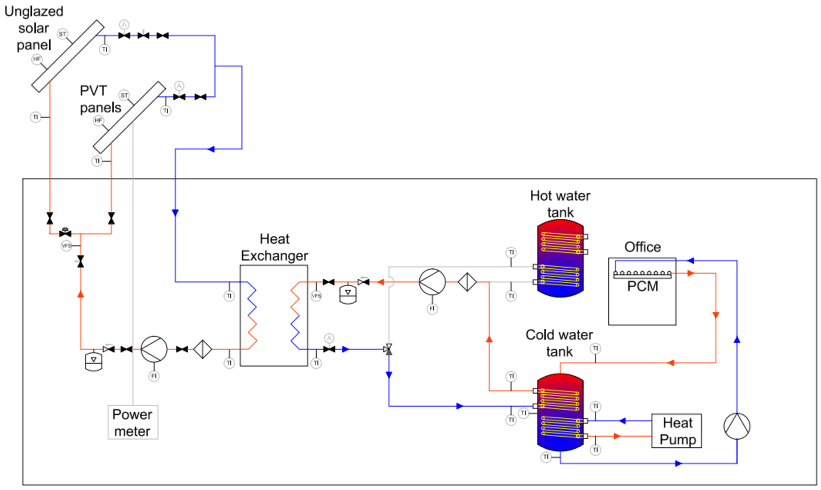

Figure 2. Schematic drawing of the system

RESULTS

In Table 1 the percentages of the occupancy period where the operative temperature was within the limits of each category of EN 15251 (DS/EN, 2007b) are presented. The temperature should be within the ranges 23.5 – 25.5°C, 23 – 26°C and 22 – 27°C (74.3 – 77.9°F, 73.4 – 78.8°F and 71.6°F – 80.6°F) for Category I, II and III, respectively.

Table 1. Percentages of Occupancy Period in Categories of Standard EN 15251

City	Category I, %	Category II, %	Category III, %
Copenhagen	27	40	63
Milan	30	44	81
Athens	26	53	82

It can be seen that Athens had the highest percentage of occupancy time with an operative temperature within the range of Category III. For Milan, the portion of time with thermal conditions within Category III was 1% less than in Athens. Copenhagen had significantly lower percentage of occupancy period within the range of Category III compared to the other two cities.

In Table 2 the average power per m² of the PV/T panels in terms of production of electricity, hot and cold water in the three simulated cities is presented. The highest average electrical power was obtained in Athens, while the average hot and cold water production power was measured in Milan and Copenhagen, respectively.

Table 2. Average Power of the PV/T Panels

City	Average electrical power, W/m² (Btu/h.ft²)	Average hot water production power, W/m² (Btu/h.ft²)	Average cold water production power, W/m² (Btu/h.ft²)
Copenhagen	26.6 (8.4)	76.1 (24.1)	42.8 (13.6)
Milan	27.5 (8.7)	108.2 (34.3)	35.9 (11.4)
Athens	32.6 (10.3)	95.0 (30.1)	33.4 (10.6)

In Table 3 the average power per m² of the unglazed solar collector in terms of hot and cold water production in the three cities is presented. The negative values of power for the production of the cold water mean the water was warmed up instead of cooled down.

Table 3. Average Power of the Unglazed Solar Collector

City	Average hot water production power, W/m² (Btu/h.ft²)	Average cold water production power, W/m² (Btu/h.ft²)
Copenhagen	55.4 (17.6)	-9.4 (-3)
Milan	63.1 (20)	-2.3 (-0.8)
Athens	66.7 (21.1)	8.0 (2.5)

In Figure 3 the percentage of cooling energy provided by night-time radiative cooling and the chiller is shown. Night-time radiative cooling had the highest potential in Copenhagen, while the lowest cooling energy was achieved in Athens.

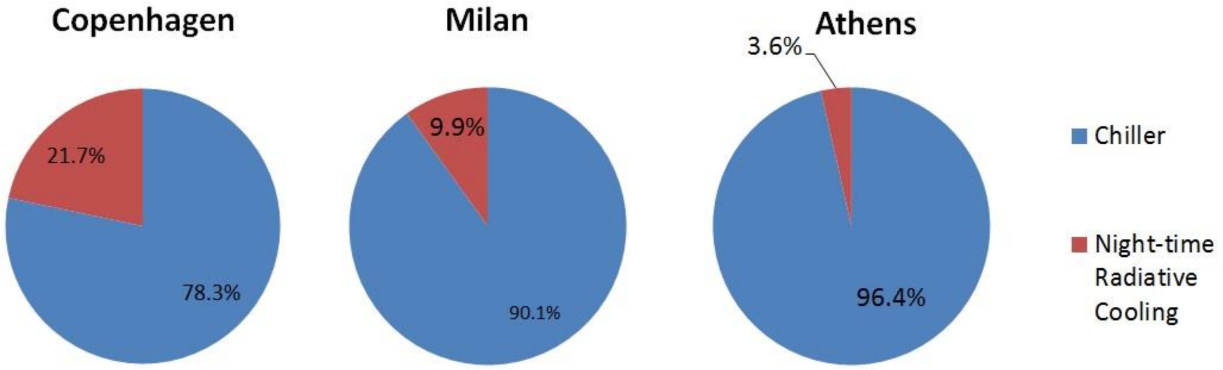

Figure 3. Percentage of cooling energy provided by night-time radiative cooling and the chiller

In Figure 4 the comparison between the electrical energy production and electrical energy usage of the three cities is presented. The latter is tabulated separately for the office equipment, the pumps, the ventilation and the chiller. The energy usage of the office equipment was always 279.1 kWh, 952000 Btu. The pumps bar represents the energy usage of all three pumps shown in Figure 2. The solar loop pump was operated continuously, while the operation of the other two pumps differed based on the weather conditions of each city. The total energy usage of the three pumps varied slightly from 52.8 kWh 180000 Btu for Milan and Athens to 53.2 kWh 181000 Btu for Copenhagen. The ventilation bar includes the energy usage of the fan and the cooling coil. For the fan, a specific fan power (SFP) of 1000 W/(m³/s), 96.6 Btu(ft³/s) was assumed, which corresponds to Category SFP 3 of DS/EN

13779 (DS/EN, 2007a). The energy usage of the ventilation system was 49.1 kWh, 168000 Btu for all three cities. The electricity usage of the chiller was 178 kWh (607000 Btu) in Copenhagen, 268 kWh (914000 Btu) in Milan and 388 kWh (1324000 Btu) in Athens. The electrical energy production from the PV/Ts for the simulated period was 371 kWh or 94.4 kWh/m^2 of PV/T area (1266000 Btu or 29900 Btu/ft^2) for Copenhagen, 380 kWh or 96.7 kWh/m^2 (1297000 Btu or 30700 Btu/ft^2) for Milan and 439 kWh or 111.7 kWh/m^2 (1498000 Btu or 35400 Btu/ft^2) for Athens. The percentage of electricity usage covered from PV/Ts was 66% in Copenhagen, 58% in Milan and 57% in Athens.

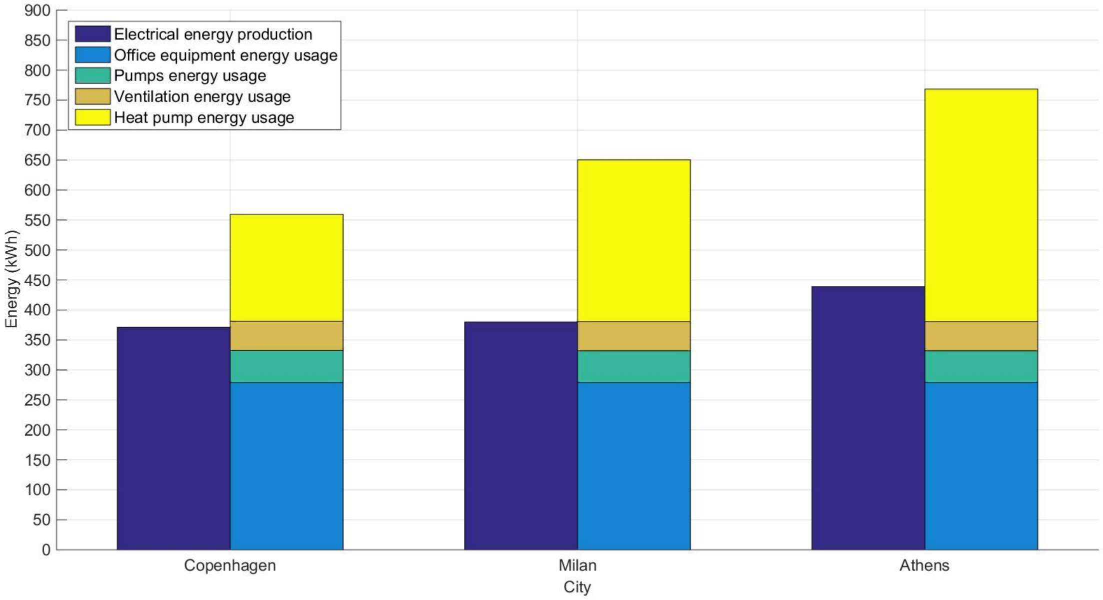

Figure 4. Energy Production and Usage Comparison

DISCUSSION

Analyzing the results shown in Table 1, it may be seen that Copenhagen had the lowest percentage of occupancy time within the range of Category III out of the three examined cities. This is because of the high solar heat gains in Copenhagen due to the low average elevation angle of the sun at this latitude. This can be seen in Figure 5, where the peak value per day of solar heat gains for the three cities is presented. It can be seen that the values simulated in Copenhagen, for most of the simulated days are considerably higher than the values measured in Milan and Athens. In these simulations no solar shading system for the windows was used, since it was not attempted to minimize the cooling demand by means of improving the envelope but intended to examine the performance of the systems as the building was given. If a solar shading system was used, the thermal conditions in all three cities would improve.

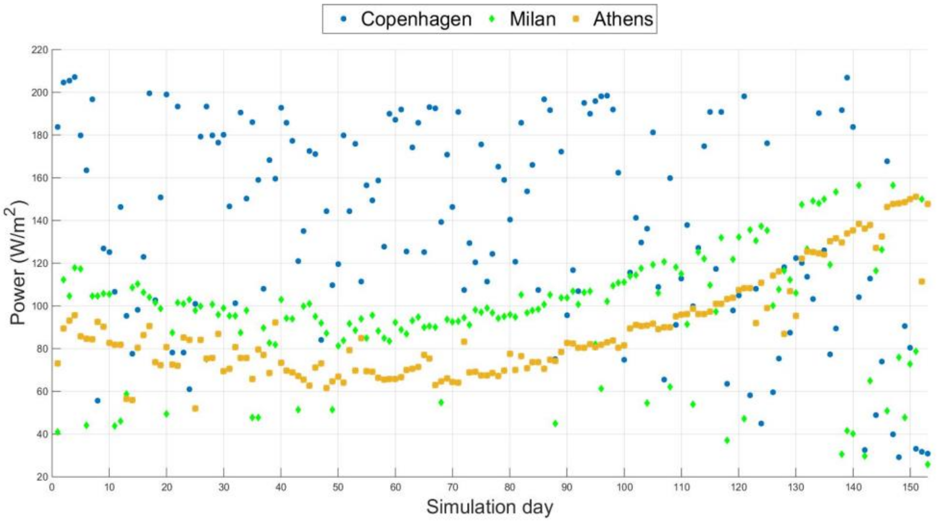

Figure 5. Solar Heat Gains Daily Peak Value

The properties of the PV/T panels and the unglazed solar collector (water flow rate, tilt angle and orientation) remained the same for the three cities. Therefore, the considerable differences observed in the values shown in Table 2 and Table 3, were caused by the different weather conditions the panels were exposed to in the three cities. The results of the unglazed solar collector in Copenhagen and Milan, shown in Table 3, indicate that the temperature of the water was increasing during the night. A better performance of the night-time radiative cooling would thus be achieved if in these two cities only PV/T panels were used.

In Figure 3 it can be seen that Copenhagen has the highest percentage of cooling energy provided by night-time radiative cooling, while Athens has the lowest percentage, almost negligible. The heat exchange of the solar collectors is a combination of radiation towards the sky and convection between the air and the surface of the collectors. Radiation towards the sky resulted in heat losses in all three cities. The air temperature was lower than the collectors' surface temperature only in Copenhagen resulting in heat loss in Copenhagen and heat gain in Milan and Athens. That resulted in the limited performance of the night-time radiative cooling in Milan and Athens. That was the reason why the performance of the unglazed solar collectors in terms of producing cold water through night-time radiative cooling was negligible.

The simulation model was designed in a way to examine mainly the performance of the night-time radiative cooling principle for solar collectors, so the hot water stored in the HWT was not utilized, as it was mention in the "Method" chapter. During a sunny day the temperature in the HWT was increasing considerably. Since the hot water was not utilized, the only temperature drop in the HWT was caused by heat losses. Therefore, the following day the pump placed after the heat exchanger would hardly be activated since Condition (1) would not be fulfilled, even if the weather conditions were suitable for producing hot water. This resulted in underestimating the performance of the solar collectors in terms of domestic hot water production.

In Figure 4 it can be seen that Athens is the city with the highest electricity production from the PV/T, as expected. In spite that, due to the negligible production of cooling energy from the night-time radiative cooling, the use of the chiller was significantly higher compared to the other two cities, resulting in the lowest percentage of electrical energy usage covered by the production from the PV/T panels. On the other hand, in Copenhagen the use of the chiller was considerably lower; resulting in a higher fraction of electrical energy usage covered by the production from the PV/T panels. Although in all the three simulated cities the electricity production from the PV/Ts did not cover completely the electrical energy demand, it should be taken into consideration that the production of hot and cold water from the PV/Ts would reduce the operation time of the heat pump. If a water-to-water heat pump or a ground source heat exchanger was used instead of an air-to-water heat pump a higher COP would be achieved and the use of the heat pump would be reduced. The considerable differences in terms of electrical energy production and chiller energy usage observed between the three cities can be explained by the different climates to which the panels were exposed in the different locations.

As it was mentioned in the "Method" chapter, the circulation of the water in the PCM panels was activated from 20:00 until 09:00 while the heat pump was activated from 00:00 until 09:00. This gave only a limited amount of time for the exploitation of night-time radiative cooling before the heat pump was activated. A time schedule that may improve the performance of the solar collectors in terms of cooling energy production would be to activate the PCM and the heat pump later during the night, e.g. at 05:00 until 9:00. In this way the night-time radiative cooling could be exploited for a longer period, and the use of the heat pump could be reduced. This control method will be addressed in a later study.

CONCLUSIONS

1) The PCM ceiling panels provided better thermal conditions in Athens and Milan than Copenhagen due to the position of the sun during daytime. 2) The cooling power of the unglazed solar collector was negligible and in Milan and Copenhagen a better performance would have been achieved if only PV/T had been used. 3) Night-time radiative cooling covered a higher percentage of the cooling demand at higher latitudes in spite of the lower percentage of clear sky. 4) Higher fraction of energy usage was covered by the production from the PV/Ts in Copenhagen than Milan and Athens. 5) The performance of the installations could be improved by implementing a solar shading system on the window and an improved control strategy, as described at the end of the "Discussion" chapter.

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