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COOLING LOAD REDUCTION WITH TRANSPIRED SOLAR COLLECTORS

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Highlights

- Cooling load reduction
- The passive cooling potential of transpired solar collector
- At night, the perforated plate acts as a radiating shield

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Abstract

When considering energy reduction issues of the building sector, one cannot overlook the importance of cooling load reduction. Depending on a country's primary energy conversion factor, producing one unit of cooling energy with a chiller can require three times as much primary energy than producing one unit of heating energy with a boiler. A remarkable amount of the cooling load of a building reaches the interior through the roof, as roofs can be as hot as 70 °C under strong solar radiation. Roof ventilation with double-layer structures offers a reliable temperature reduction between the solar exposed upper layer and the lower one, which is the actual building roof. The transpired solar collector (TSC) is a proven technology for solar air heating with numerous installed and successfully operated systems around the world. This paper reflects on its passive cooling potential, when the perforated metal plate absorber is installed on a building's roof. At night, the perforated plate acts as a radiating shield, which loses heat towards the cold sky. The perforated plate cools below ambient temperature and cools transpiring outdoor air which is later used for nocturnal ventilation of the building. However, the predicted cooling energy during an analysis of the radiant cooling strongly depends on the sky temperature model chosen. Different models of sky temperature are compered in their result on the longwave radiant heat flux towards the sky. The comparison has been carried out for four cities with different climate. Results reflect on a novel application of the transpired solar collector, which therefore can be used for the reduction of building energy consumption over the entire year.

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1. Introduction

As the building sector is responsible for 40-50 % of the energy consumption in the EU (Kolokotroni, Aronis, 1999), in order to accomplish the 20/20/20 targets of the Energy Efficiency Plan of 2011 (www.eea.europa.eu/highlights/eu-achieves-20-20-20), it is crucially important to apply energy supply systems which use renewable sources of energy. Transpired solar collectors are economical systems to include renewable energy supply into the heating system of a building.

However, the production of a unit of cooling energy can require multiple amounts of the production of one unit of heating energy, depending on the primary energy conversion factor of the country. This makes cooling demand reduction even more important than the reduction of heating demand. A vast proportion of building cooling load arrives through the roof. Ventilated double shell roofs can efficiently reduce the temperature of the ceiling and thus the cooling load. Al-Obaidi et al. (2014) designed an innovative roofing system to reduce heat gain using reflective and radiative pigment technique, as well as ventilation. Results show that the developed roofing system was able to reduce the indoor air temperature compared with conventional roofing system by approximately 2.1°C under daylight condition. Roslan et al. (2016) wrote that "it is natural to expect that an unvented roofing system would affect the energy consumption of a house". Ciampi et al. (2005) investigated the convenience of using ventilated roofs for the reduction in summer thermal loads, taking into consideration the case of roofs with small-sized-thickness duct in which the airflow is laminar (microventilation). The obtained results show that an energy saving, even exceeding the 30%, can be achieved by using ventilated roofs in summer, compared to the same non-ventilated structure. Puangsombut et al. (2007) carried out experimental investigation on the natural ventilation flow rate and heat gain reduction in an attic using an open-ended inclined rectangular channel with radiant barrier. When compared to a conventional roof solar configuration with gypsum board on the lower part, it was observed that the use of radiant barrier increased convective heat transfer and airflow rate by about 40–50%, thereby increasing heat transfer reduction through the lower plate by about 50%. Results show that extensive research have been made on the cooling load reduction with ventilated roofs. However, none of them investigated roof ventilation with the commercially available TSC.

2. Transpired Solar Collectors

Transpired solar collectors are commonly used systems for solar air heating in North America and they are getting more widespread in Europe, too. Primary energy can be reduced with their application in every building with high fresh air demand and enough space on the façade for their installation. Mainly large halls like commercial and industrial buildings meet these criteria, as both manufacturing processes and the storage of certain goods can require ventilation with fresh air. (Hollick J, 1994)

2.1. Construction and Operational Principle

The potential of the transpired solar collector lays in its simple construction and thus reliable and almost maintenance-free operation. The absorber, which is made of conventional building cladding material, can be included in the in the architectural conception of new buildings, but it can be added to existing facades, too. The trapezoidal, perforated metal shield is mounted in 15-20 cm distance onto the building's original façade, creating an air gap, or plenum. This is closed from the sides, so air can enter it only through the perforations of the absorber plate.

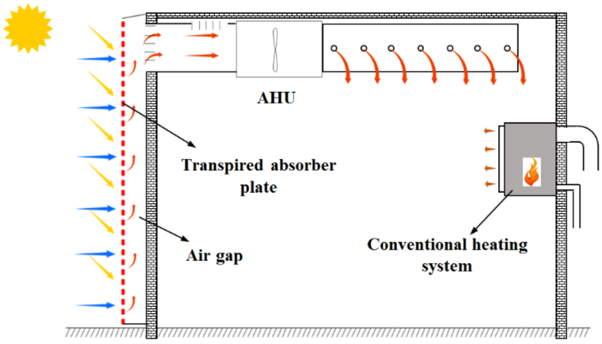

Figure 1. TSC construction and operational principle

As Figure 1 shows, the air passes the absorber as AHU fans withdraw fresh air from the plenum. The transpiration of the absorber ensures the transfer of the solar heat to the fresh air. The simple construction and maintenance free operation of the TSC ensures low payback periods such as 2-10 years (Hall at al., 2011), which is remarkably low among solar thermal systems.

2.2. Physics of Solar Air Heating with TSC

Seeing Figure 1, one could think that in the lack of transparent glazing, the TSC has remarkable thermal losses due to convection to the exterior. According to Kutscher et al. (1993), assuming homogenous suction on the surface the absorber, one can state that the suction stabilizes the boundary layers on the external side of the absorber, reducing the effect of convective losses solely to the collector edges. This means that for large collector surfaces the convective losses are negligible and wind losses remain small, too. Kutscher et al. (1993) describe that to ensure little impact of wind:

- the suction face velocity should be preferably 0.04-0.05 m/s, but at least 0.02 m/s,
- at least 25 Pa pressure drop is to be obtained across the perforated plate, and
- the wall should be designed to have uniform flow through itself.

The flow rate through the surface of the TSC has to be kept between 18-180 $m^3/(h \cdot m^2)$ (RETScreen International, 1997-2005) to ensure stable operation. Three air heating strategies can be defined by choosing the appropriate airflow:

- high temperature rise in the range of 18-54 $m^3/(h \cdot m^2)$
- standard operation in the range of 54-108 $m^3/(h \cdot m^2)$
- high air volume in the range of 108-180 $m^3/(h \cdot m^2)$

High-flow TSC systems perform much better than low flow ones, as the efficiency can reach its highest values when high flow is cooling the absorber, utilising the most of its heat, reducing all kinds of thermal losses. In Figure 2 one can see that for a given wind speed the collector efficiency only depends on the air flow rate, which underlines the negligible impact of convective losses depending on ambient temperature.

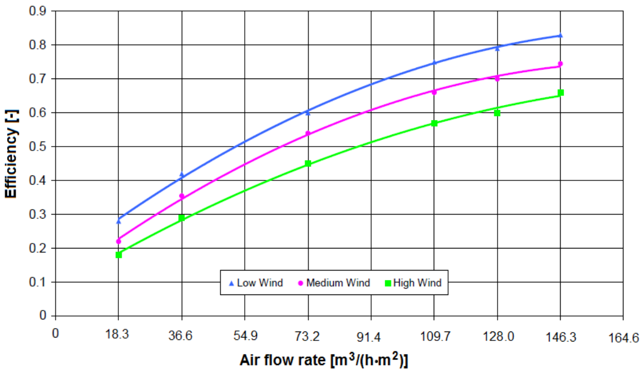

Figure 2. TSC efficiency as a function of the air flow rate (http://sahwia.org)

The decreasing collector efficiency in low flow operation defines a minimum flow rate for the solar air heating operation of the TSC. Under 18 $m^3/(h \cdot m^2)$ the uniform transpiration of the absorber plate cannot be ensured. Natural ventilation through the perforated plate and in the plenum creates an outflow in higher areas of the absorber. This is absolutely undesirable, as this collector area does not take place in the solar air heating process anymore. However, this phenomenon can be made useful when applying the TSC on a building roof.

3. Roof Ventilation with TSC

The installation of transpired solar collectors on a building roof ensures new benefits of the system. Other than one would first think, the absorbent surface which reaches high temperatures during hot and sunny summer days does not increase the cooling load of the building. The natural airflow described above comes to be too, if the collector is not installed for solar air heating purposes, but simply as a ventilated, double roof structure.

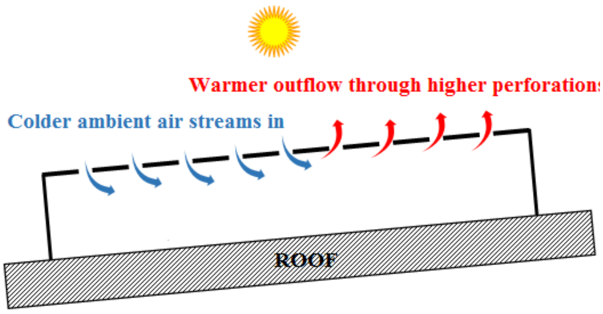

Figure 3. Natural ventilation in a roof mounted TSC

The absorber plate, which reaches high temperatures, evokes the natural airflow in the air gap between the absorber and the original roof. The air in the cavity rises driven by buoyancy the force, leaves through upper perforations and at the same time colder ambient air streams into the air gap beneath. The described process is visualized in Figure 3. The continuous ventilation thermally decouples the absorber plate from the back plate which stands for the actual building roof. The TSC reduces thermal load from the building roof this way, which is proven by the experimental research carried out by Bokor et al. (2017).

An experimental setup of 5 m^2 TSC with adjustable tilt of 0-10-20-30-40 ° (see Figure 4) was used to investigate the cooling load reduction capacity of the TSC. Measurements were carried out in summer 2016 on the campus of Trakya University, Engineering Faculty, Edirne, Turkey. Results show that the TSC is capable to reduce heat gain between the absorber plate and the back plate to 4-12 % of the incoming solar radiation in average.

Figure 4. The 5 m^2 experimental setup used for roof ventilation measurements

4. Nocturnal Radiant Air Cooling with TSC

Several studies (Artmann et al. 2007, Kolokotroni et al., 1998, Blondeau, et al., 1997) have emerged about cooling load reduction by nocturnal ventilation of buildings. By natural or mechanical ventilation buildings are supplied by cool ambient air during the night, which aims to reduce the temperature of the building mass. For this, a remarkable temperature difference is necessary between the building mass and the ambient air. Considering the climatic conditions in Europe, one can state that in regions with warm climates such as the Mediterranean basin where the higher cooling peaks come to be, it is less likely to find cool enough nocturnal ambient temperatures.

The efficiency of the cooling load reduction with nighttime ventilation can be increased if the ventilation air is cooled below ambient temperature using any passive cooling method. Sky facing transpired solar collectors can be used as radiating shields which cool down below ambient temperature. Hollick (2012) carried out night cooling tests with commercially available TSC absorbers and obtained results which show that the plate “can be approximately 10 °C cooler than ambient temperature in the Great Lakes region”, cooling ambient air “by as much as 4.7 °C below” its original temperature.

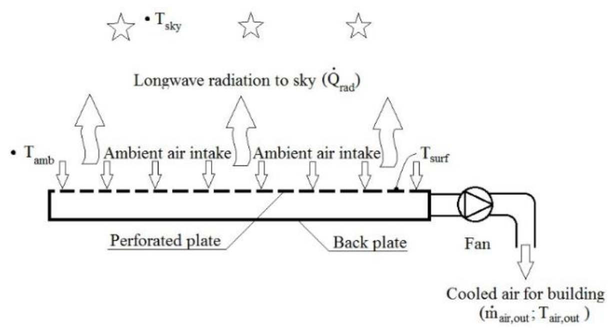

Figure 5. Physical model of nocturnal radiative air cooling with a transpired solar collector

Figure 5 shows the physical model of the nocturnal radiant air-cooling method using TSC. It is to be noted that unless the absorber surface of a solar collector has been selectively coated, not only its absorptivity (α), but also its emissivity (ε) value is high (Hall and Blower, 2016). In the current investigation ε = 0.77 was considered, which is common for commercially available transpired solar collectors.

The longwave radiant heat transfer between the collector surface and the cold night sky can be calculated using eq. (1) as given by Kumar and Leon (2007).

$$\dot{Q}_{LW} = \varepsilon_{col} \cdot \sigma_{SB} \cdot A_{col} \cdot \left(T_{col}^4 - F_{cs} \cdot T_{sky}^4 - F_{cg} \cdot T_{gnd}^4\right) \quad (1)$$

Here T_{col} is the collector temperature in K, T_{sky} is the equivalent sky temperature in K, T_{gnd} is the ground temperature in K, while F_{cs} and F_{cg} are view factors given by eq. (2)-(3).

The collector-sky view factor is:

$$F_{cs} = \frac{1 + cos\gamma}{2} \quad (2)$$

Here γ stands for the collector tilt.

The collector-ground view factor is:

$$F_{cg} = 1 - F_{cs} \quad (3)$$

For the determination of the equivalent sky temperature several models are available. In the following section it is shown how different sky temperature models influence the calculated longwave radiant heat flux, which powers the nocturnal air-cooling process of a TSC.

4.1. Clear Sky Temperature Calculation Models

The general equation of the clear sky temperature (eq. 4.) defines it as a function of the ambient air temperature in K (T_{amb}) and the clear sky emissivity (ε_{sky}).

$$T_{sky} = T_{amb} \cdot \varepsilon_{sky}^{0.25} \quad (4)$$

For the clear sky emissivity several studies have delivered correlations. Pioneering studies of Angstrom and Brunt delivered correlations which contain empirical coefficients which depend on the geographical location (Vall and Castell, 2017). Swinbank (1963) developed a correlation which delivers the clear sky temperature solely depending on the ambient temperature.

$$T_{sky} = 0.0552 \cdot T_{amb}^{1,5} \quad (5)$$

Hatfield et al. (1983) stated in their study that models which do not consider the effect of humidity only that of the ambient temperature do not estimate the sky emissivity in a precise manner.

Bliss (1961) developed a correlation (eq. 6.) which is based on theoretical concepts of gas emissivity and empirical correlations of gas properties (Vall and Castell, 2017).

$$\varepsilon_{sky} = 0.8004 + 0.00396 \cdot t_{dew} \quad (6)$$

Clark (1981) developed the correlation below based on dew point temperature too:

$$\varepsilon_{sky} = 0.787 + 0,0028 \cdot t_{dew} \quad (7)$$

Berdahl and Fromberg (1982) developed correlations for both day and night based on measurements in three cities in the USA. Eq. (8) predicts the nighttime sky emissivity.

$$\varepsilon_{sky,night} = 0.741 + 0.0062 \cdot t_{dew} \quad (8)$$

Berger (1984) carried out measurements in Carpentras, France and laid down all-day and nocturnal correlations from which here the latter is considered as eq. (9):

$$\varepsilon_{sky,night} = 0.770 + 0.0038 \cdot t_{dew} \quad (9)$$

Based on measurements on the Negev Highlands in Israel, Tang et al. proposed the following formula:

$$\varepsilon_{sky} = 0.754 + 0.0044 \cdot t_{dew} \quad (10)$$

Berdahl and Fromberg (1982) derived the sky temperature from the ambient temperature T_{amb} in K, the dew-point temperature in °C and the hour from midnight τ in eq. (11):

$$T_{sky} = T_{amb} \cdot [0.711 + 0.0056 \cdot t_{dew} + 0.000073 \cdot t_{dew}^2 + 0.013 \cdot \cos(15\tau)]^{1/4} \quad (11)$$

To see the effect of the sky temperature/emissivity model choice, a comparison has been made between for cities with different climates. The meteorological data has been obtained from RETScreen 4 Clean Energy Project Analysis Software, as well as (www.weatherbase.com/weather). The locations chosen are a) Bamako, Mali, b) Tunis, Tunisia, c) Milan, Italy and d) Hamburg, Germany.

Bamako, Mali has tropical savannah climate where average daytime temperatures range between 24-30°C. There is a yearly swing in relative humidity marking a dry season from November to April with almost no precipitation and a rainy season From July to September. As seen in Figure 6a) there is cooling season in the entire year. The lower sky temperatures in the winter months are the result of the dry season when the low amount of atmospheric humidity enables sky temperatures to reach lower values. Figure Figure 7a) shows the calculated sky temperatures. It can be seen that the Swinbank equation – the only one which does not consider atmospheric humidity – delivers the highest values in the dry season and the lowest ones in the rainy one. On the other hand, it can be stated that all other models which incorporate humidity, result in colder skies when the atmosphere is dry and warmer ones in the humid rainy season.

Figure 8 shows the calculated longwave radiation from a horizontal surface of ambient temperature using eq. (1). As the plate cools down below ambient as a result of the radiative heat transfer, these values get smaller. However, Figure 8 is still suitable for demonstrating the yearly course of the longwave heat flux calculated using different methods. It can be observed on Figure 8a) that for Bamako the Swinbank equation predicts remarkably less radiant heat flux to the sky for the dry and more for the humid season. The yearly course of the other models is similar, however there are significant differences between the results which reflects on the importance of choosing the suitable model. This can be found by a comparative analysis with measurement results only. Bamako has a visibly different course of longwave flux compared to the other three cities, which is due to the high changes in humidity in the Malian capital. For the dry season, the model of Martin and Berdahl predicts 50 % of longwave flux of that of the dry season. In other cities the yearly course of the LW profiles is more balanced.

Tunis, Tunisia has hot summer Mediterranean climate with hot and dry summers and mild winters. As seen in Figure 6b) the cooling season in Tunis still expands to the whole year, however in the winter months the cooling degree days reach only a tenth of the peak values in summer. The different models for the clear sky temperature deliver much more correlating values for Tunis than for Mali, this is due to the smaller change in relative humidity over the year. As Figure 8b) shows balanced values for the yearly course of longwave radiation with the highest values in the winter time, one can state that nocturnal radiant cooling with TSC could possibly take a remarkable share in the cooling energy demand in winter and in the transitional period, but could also reduce peaks in summer.

Milan has humid subtropical climate with hot summers and foggy winters. The cooling season lasts from April to October. As the sky temperature depends on the ambient temperature, it can be seen that the locations with colder ambient temperatures consequently have lower night sky temperatures.

In Hamburg there is oceanic climate due to the vicinity of the Noth and Baltic Seas. Winters are cold, but snow is rare. Summers are mild, the cooling season restricts only to a period from May to September with low peaks. The theoretically calculated longwave radiant heat flux towards the sky can be significantly reduced by the often-thick cloud cover, which is not taken into consideration in the present study.

The considered models result in remarkable differences in longwave radiation for the examined locations. For Tunis, Milan and Hamburg the lowest heat flux is resulted by the model of Bliss. The highest one remains Swinbank's solution for Tunis, Milan and Hamburg. However, the difference between minimum and maximum is remarkable: for Hamburg the average of the results delivered by Bliss' model is 2/3 of the results of the Swinbank equation.

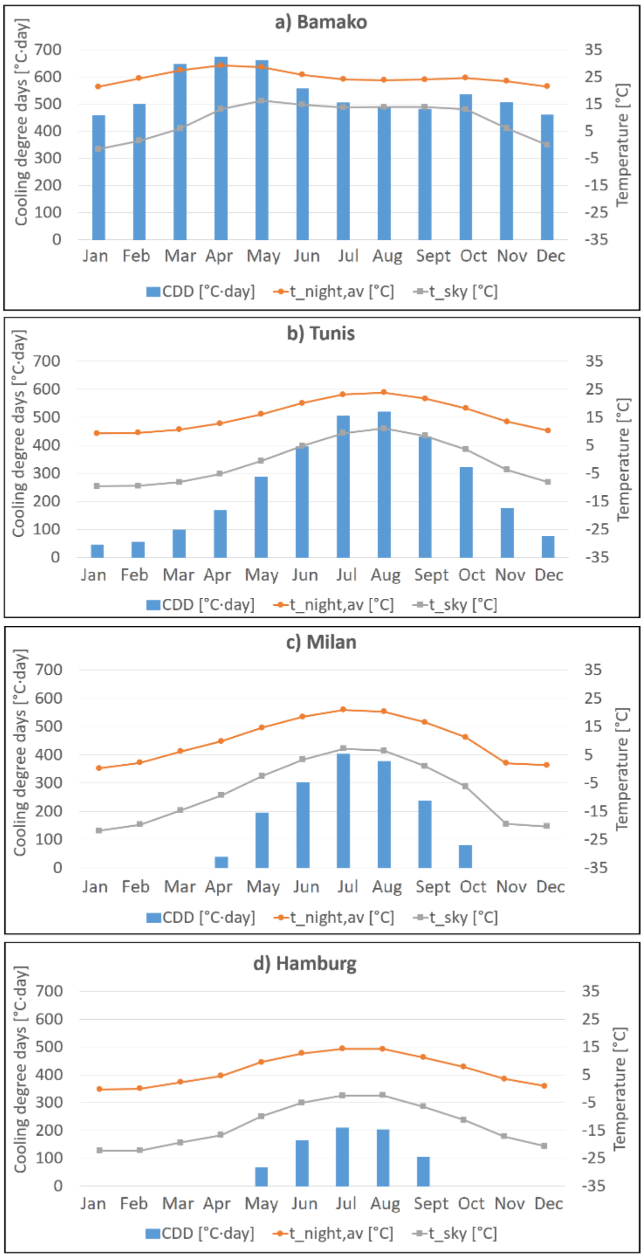

Figure 6. Monthly values of cooling degree days, nocturnal average temperature and sky temperature for Bamako, Tunis, Milan and Hamburg

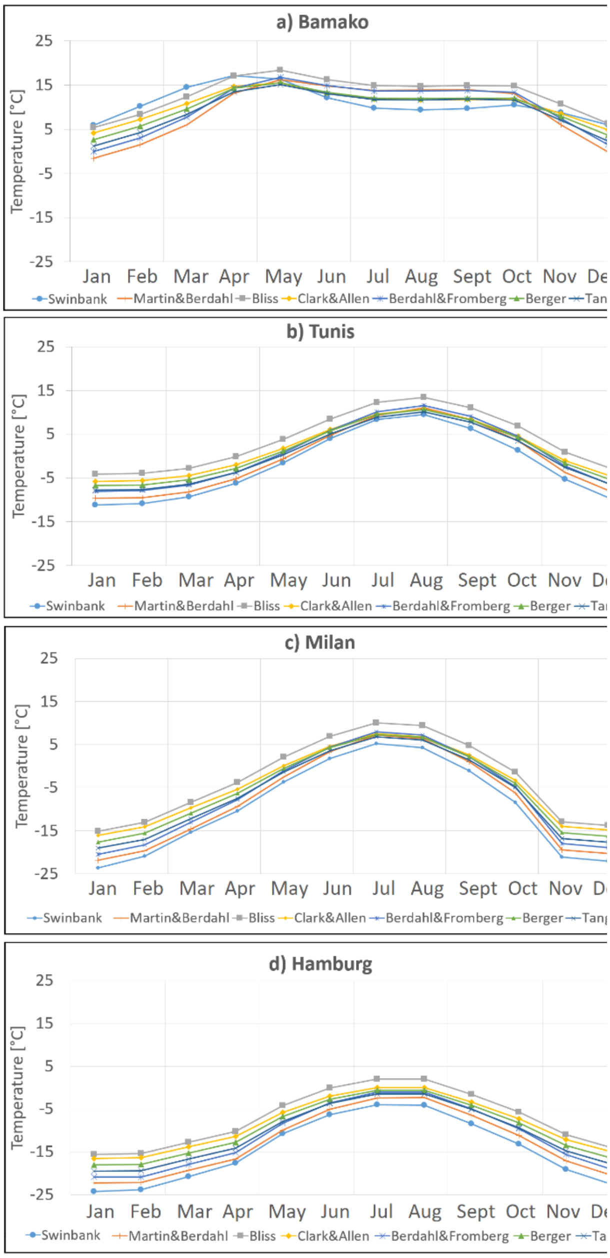

Figure 7. Monthly average nighttime clear sky temperatures for Bamako, Tunis Milan and Hamburg calculated according to the named correlations

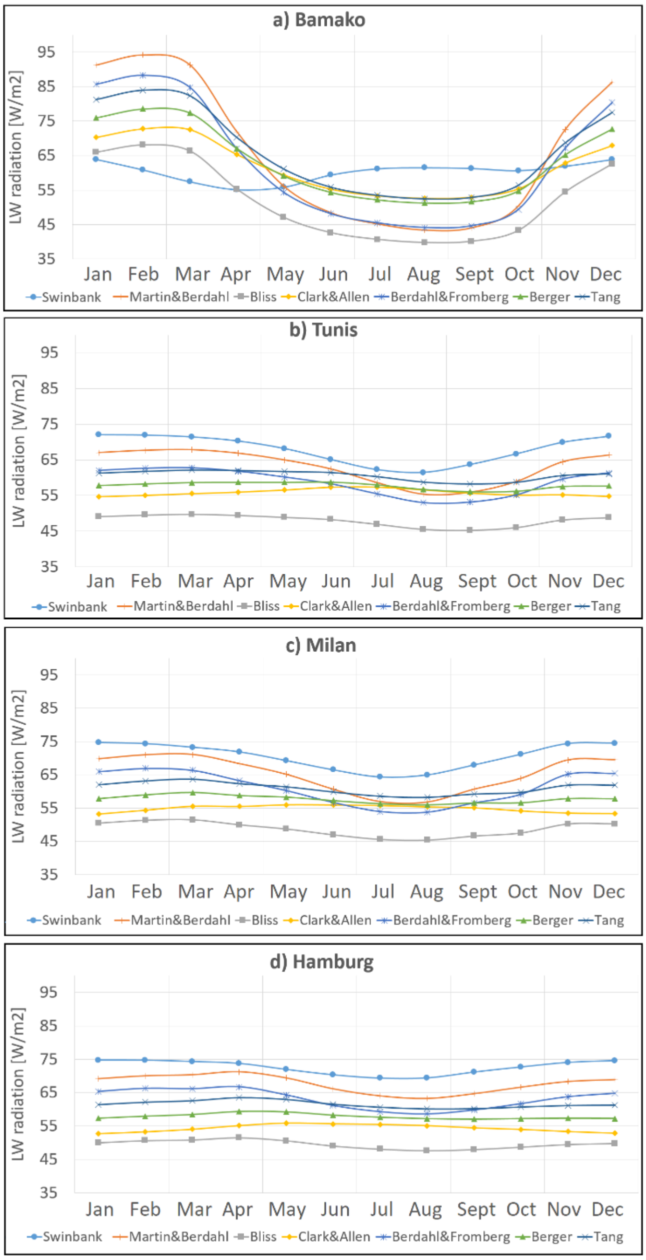

Figure 8. The effect of different T_{sky} models on the monthly average LW radiation from a horizontal plate of ambient temperature.

5. Conclusion

Transpired solar collectors are reliable solar thermal systems, which can reduce the primary energy consumption of a building over the whole year. Their simple construction and maintenance-free operation result in short payback periods. They have been successfully applied for solar air heating since the early 1990s, but the current research reflects on their ability to reduce the cooling load of a building in summertime.

Experimental and theoretical research has shown that the transpired solar collector is capable to reduce heat gain between the absorber plate and the back plate to 4-12 % of the incoming solar radiation in average.

Different clear sky emissivity and temperature models have been compared in their effect on the longwave radiant heat flux towards the sky from a horizontal plate of ambient temperature. It must be noted that the applied models calculate clear sky emissivity and temperature. Occasional cloud cover significantly reduces the longwave radiant heat flow towards the sky. However, the effect of cloud coverage is out of the scope of the current investigation.

Although the sky temperatures are often close and vary by a few degrees in the summer months as seen on Figure 7 b) c) and d), the changes in longwave radiation become remarkable between results delivered by the different models.

It can be seen that the Swinbank equation does not always deliver the lowest sky temperatures, when the atmosphere is extremely dry like during the dry season in Bamako, it resulted in the highest sky temperatures.

Based on the current investigation it can be concluded that the longwave radiation to the sky reaches the highest potential during the dry season in Mali which has the hottest climate of the four examined locations. This result highlights on the need of further research to investigate the possibly quick payback of the low budget TSC alongside with its passive cooling fraction in the entire cooling demand.

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