International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:13, No:10, 2019

The Influence of Meteorological Properties on the Power of Night Radiation Cooling

Othmane Fahim, Naoual Belouaggadia. Charifa David, Mohamed Ezzine

Abstract**—**To make better use of cooling resources, systems have been derived on the basis of the use of night radiator systems for heat pumping. Using the TRNSYS tool we determined the influence of the climatic characteristics of the two zones in Morocco on the temperature of the outer surface of a Photovoltaic Thermal Panel "PVT" made of aluminum. The proposal to improve the performance of the panel allowed us to have little heat absorption during the day and give the same performance of a panel made of aluminum at night. The variation in the granite-based panel temperature recorded a deviation from the other materials of 0.5 °C, 2.5 °C on the first day respectively in Marrakech and Casablanca, and 0.2 °C and 3.2 °C on the second night. Power varied between 110.16 and 32.01 W/m² marked in Marrakech, to be the most suitable area to practice night cooling by night radiation.

Keywords**—**Morocco, TRANSYS, radiative cooling.

I. Introduction

In Morocco, the building sector is one of the most energy-consuming and energy-producing sectors, and there is an urgent need to introduce energy-efficient practices [1]. Night radiation is an important meteorological phenomenon, based on the loss of heat to the atmosphere [2]. In the night and because of the absence of solar rays, the atmosphere cools, the earth seeks to achieve its thermal equilibrium with its surroundings by yielding most of its heat which it received during the day in a radiative and convective way. This exchange of heat from the earth to the celestial vault "from the warm body to the cold body", produces a cooling effect that can be exploited to cool the buildings during the day. There are several techniques that can use the phenomenon of night radiation to cool buildings, like cooling by moving insulation, or the use of selective emitter materials that have a high technical potential for radiative cooling applications [3]. Also among the systems used to produce cold, hybrid systems are a good alternative, which allow to store «cold» using the freshness of the night and thus to decrease the requirements for mechanical air conditioning [4]. This technique is based essentially on three stages of production, storage and distribution. Production is done through hybrid panels that are radiant panels placed on roofs or walls to enjoy the low temperature of the celestial vault at night. The fluid that cools through circulation in the panel is stored in a tank, which must be well insulated to keep its low temperature. The distribution of the cold fluid is done with tubes integrated in the roof to absorb the heat of the building.

Fahim Othmane is with the Hassan II University of Casablanca, Morocco (e-mail: othmanefahim@gmail.com).

In this article, we focused our attention first on a comparative study between the performance of the proposed material and the material most often used in the manufacture of the outer surface of the hybrid panel, for this purpose we used climatic data from two zones in Morocco that have different meteorological properties and also to determine the influence of its data on the temperature of the outer surface of the panel.

We were able to obtain the ambient temperature variation, the sky temperature and the outside surface temperature of the two panels, respectively, for 48 hours of the test "July 14 to 16". First, we proposed to work with an aluminum panel, which is most often considered in the manufacture of thermal panel. About the second one, we proposed to use a panel also made of aluminum but with a thin layer of white granite on its outer surface. In a second step, and in order to complete the most efficient material we determined the resulting cooling power of the temperature variation in three cases "clear skies, partially cloudy skies, and in cloudy skies". Subsequently, a comparative study enabled us to detect the area whose meteorological conditions favour a good performance of our panel.

II. Description of the Panel

In general, radiant cooling panels are panels with integrated water pipes and are attached to the construction by hangers.

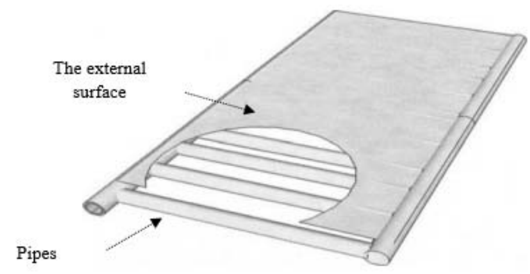

Fig. 1 Template of a Radiator Panel [5]

Technically, ceilings and walls can be used to attach radiant panels. In practice, however, the most radiant cooling panels are suspended from the ceilings. Radiant panels are generally designed as small modular units in a metal frame structure. To meet acoustic requirements, these panels can be punctured to make the ceiling absorbent when acoustic materials are installed at the rear of the panels. If space cooling does not require fully covered radiant panels, conventional acoustic panels may be used with radiant panels to meet the acoustic requirements of the ceiling.

The convective exchange that is made between the fluid used and the signs of the panel, it will decrease the temperature of the latter. This fluid must pass through the panel tubes and cool thanks to its low temperature, to consolidate them in a tank that must be well insulated to be reused in the cooling of buildings during the hot periods of the. The performance of this type of panel is based on several major factors:

- The choice of materials from the outer surface which must be a more emissive material in the medium infrared;
- The choice of tube material that must be characterized by very high conductivity;
- Selecting tube diameters
- Spacing between tubes

TABLE I
PHYSICAL THERMAL PROPERTIES OF ALUMINUM AND WHITE GRANITE [6], [7]

Property	Aluminum	White granite
Density, Kg/m^3	2650	2698
Porosity	3%	11%
the water absorption coefficient	1.8	3.4
speed of sound propagation, m/s	500	6400
compressive resistance, MPa	5	5
tensile strength, MPa	0.5	30
specific heat, J/Kg	834	897
thermal conductivity, W/(m.K)	3.0-3.4	2.37
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As mentioned above, the choice of material of the outer surface of the panel is a major factor in calculating its performance with respect to night cooling. For this purpose, we proposed to compare the temperature variation of the outer surface of the two panels made of white granite and aluminum, the latter known as the most common material in the manufacture of thermal panels. The choice of white granite, here, is based on a previous comparative study [6] in which we found that this material is more efficient in night cooling [32]. In the following we used the same panel shown in Fig. 1 but with an outer surface of 1 m² and 1 mm thickness, the thermal-physical properties of the materials are presented in Table I.

III. Calculation Method

The most important part of the night cooling technique is the radiative exchange from and to the panel used [8]. There are several equations in the literature that can give the expression of the total flow of radiating energy for the outer surface of the panel which is considered grey. For example, the relationship expressed in (1) by Martin [9] is widely used in the modelling of a radiative cooling panel.

$$Q_{rad} = A_s \varepsilon_{rad} \sigma (T_p^4 - T_{sky}^4) \quad (1)$$

T_{sky} [K] is the temperature of the sky which we can express by several correlations which also depend on the meteorological properties of the study area [10]. Berger et al. [11] proposed a relationship to calculate the sky temperature based on its emission coefficient;

$$T_{sky} = \varepsilon_{sky}^{\frac{1}{4}} T_{amb} \quad (2)$$

- Emissivity according to the water vapour pressure [12]
- Emissivity according to the temperature ambient [13], [14].
- Emissivity according to the dew point (saturation) [15]-[17].

Table II represents the correlations most often used in the calculation of emissivity of the sky: The emission and absorption coefficients are given here as the spectral mean for the entire surface of the panel. The emissivity of the sky noted by T_{sky} in (2) can be calculated with several correlations prepared based on experimental results by many researchers [10], [11]. Correlations for estimating the emissivity of the sky can be grouped into three categories regardless of whether the sky is "clear, cloudy or partially cloudy".

TABLE II
CORRELATIONS OF EMISSIVITY FOR DIFFERENT SKY STATES

Clair sky		Cloudy sky	
Reference	Correlation	Reference	correlation
[18]	$\varepsilon_{cc} = 1 - 0.261 \exp[-7.77 \times 10^{-4} \times (273 - T_{amb})]$	[21]	$\varepsilon_{ciel} = (1 + 0.0496 c^{2.45}) \varepsilon_{cc}$
[19]	$\varepsilon_{cc} = 0.7 + 5.95 \times 10^{-5} e_{amb} \exp(1500 / T_{amb})$	[22]	$\varepsilon_{ciel} = (1.03 + 0.34 c) \varepsilon_{cc}$
[20]	$\varepsilon_{cc} = 1.24 \times (e_{amb} / T_{amb})^{1/7}$	[23]	$\varepsilon_{ciel} = (1 + 0.22 c^{2.75}) \varepsilon_{cc}$
[17]	$\varepsilon_{cc} = 0.770 + 0.0038 T_{dp}$	[24]	$\varepsilon_{cc} = \varepsilon_{cc} + (1 + 0.0024 n + 0.0035 n^2 + 0.00028 n^3)$

Different types of correlations allowed us to use the most suitable with the selected zones, see Fig. 2. In the following we have chosen to work by the following correlation [25]:

$$\varepsilon_{0,sky} = 0.711 + 0.56 \left(\frac{T_{dp}}{100}\right) + 0.73 \left(\frac{T_{dp}}{100}\right)^2 \quad (3)$$

To calculate the dew point temperature T_{dp}, it is not necessary to know the atmospheric pressure, we just need to the relative humidity depends on the vapour pressure and the saturating vapour pressure of the water contained in the atmosphere. We can calculate it by [25]:

$$T_{dp} = \frac{b}{[Log_{10}(RH) + \left(\frac{aT_{amb}}{b + T_{amb}}\right) - 2] - 1} \quad (4)$$

with a =7,5, b =237.3, RH= Relative humidity and T_{amb} is the ambient temperature. The emissivity of the sky in the presence of clouds is calculated by multiplying the emissivity of the clear sky by the fraction of the sky that is covered by the clouds and by the emissivity of the clouds themselves, as shown in (4) [26]. The fraction of the sky covered with opaque clouds has a value between 0 (no cloud cover) and 1 (full cloud cover). Depending on the mode of this component, the fraction of the sky covered by the opaque f_cloud clouds can be captured either as a value between 0 and 1 or as a percentage (0 to 100).

$$\varepsilon_{sky} = \varepsilon_{0,sky} + \left(1.0 - \varepsilon_{0,sky}\right) * f_{cloud} * \varepsilon_{cloud} \quad (5)$$

The emissivity of the cloud is represented in (6) by ε_cloud. This coefficient is expressed as a function of the altitude of clouds h [Km], it can be calculated by the following correlation [27]:

$$\varepsilon_{cloud} = 0.74 - 0.084(h - 4) \quad (6)$$

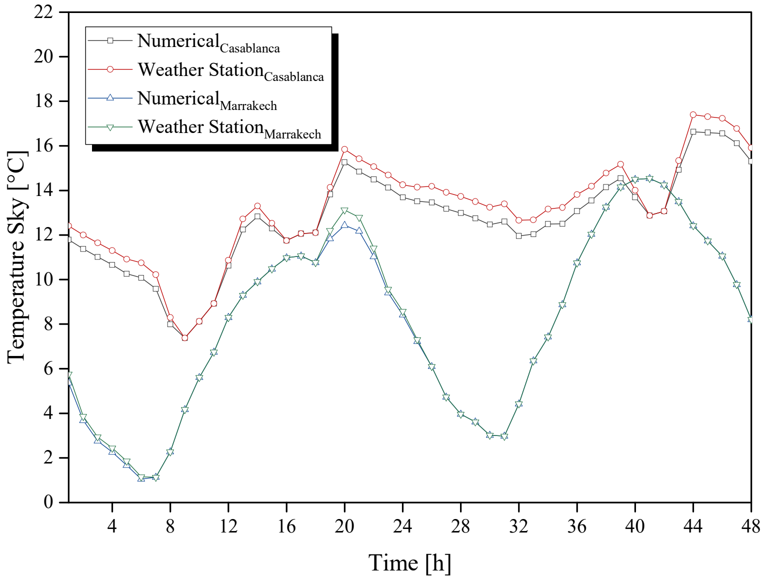


Fig. 2 Comparison of numerical results of selected correlations with meteostandard meteorological data

The convective heat transfer between the outer surface of the panel and the surrounding air also contributes to the cooling power. The heat transfer function is represented in (7).

$$Q_{conv} = A_s h_c (T_p - T_{amb}) \quad (7)$$

where h_c is a convection heat exchange coefficient expressed by [28]:

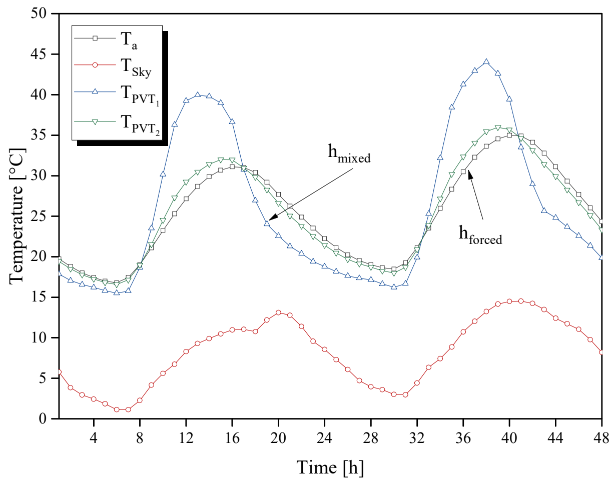
$$h_c = ({h_{nat}}^3 + \ {h_w}^3)^{1/3} \quad (8)$$

The heat transfer coefficient by forced convection h_w can be calculated using a correlation in terms of wind speed (v), as shown in (9) [28], whereas the loss of natural convection h_nat can be represented by a temperature difference between the average temperature of the outside surface of the panel T_e and the ambient temperature T_amb, as shown in (10) [29]:

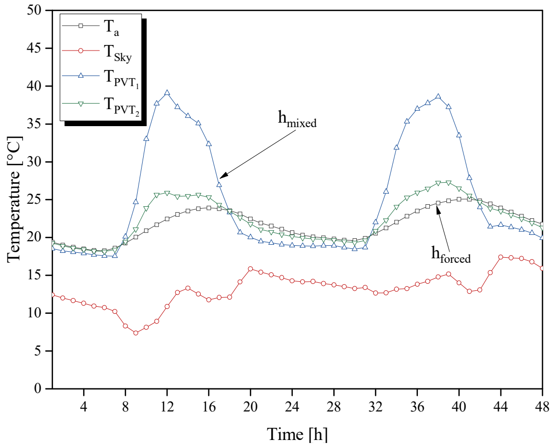
$$h_w = 2.8 + 3.0V \quad (9)$$

$$h_c = 1.78(T_e + T_{amb})^{1/3} \quad (10)$$

In July 14-16, we tested the effect of convective exchange coefficient on panel temperature in the two proposed zones, to justify the choice of correlation that we used in the calculation. Fig. 3 shows that the h_{mixed} "mixed exchange coefficient" has a very important influence on the change in panel temperature; this shows us that the $h_{natural}$ "natural exchange coefficient" has a great effect on the convective exchange with the panel.



(a)



(b)

Fig. 3 The effect of convective exchange coefficient on panel temperature at Marrakech and Casablanca respectively

By adding the convection heat transfer equation to the energy balance of the outer surface of the panel, the night-time cooling power expression becomes:

$$Q_{cool} = Q_{rad} + Q_{conv} \tag{11}$$

$$Q_{cool} = A_s \varepsilon_{rad} \sigma (T_p^4 - T_{sky}^4) + A_s h_c (T_p - T_{amb}) \tag{12}$$

IV. Geographical and Climate Data

The use of the night-time cooling technique is based essentially on the study of the meteorological properties of the areas. To have a significant cooling power, it is necessary to choose the zone which characterizes the meteorological properties adapted to this technique, we speak on the dew temperature, the humidity and the ambient temperature. In this section we propose to present the climatic characteristics of the selected zones «Casablanca and Marrakech». We start with Casablanca which is located in latitude of 33.567°, longitude of -7.667°, and an altitude 55 m [30]. The geographical positioning of Casablanca allows it to be classified in the 1st climatic zone [31]. This area is characterized by a Mediterranean climate with a strong oceanic tendency, in fact a particularly pleasant climate. According to Table III, the winters are mild and damp and the summers are temperate. The average temperature is 19 °C, but Marrakech is a city located in central Morocco, in the interior, at the foot of the Atlas Mountains in latitude of 31.630°, longitude of -8.010° and an altitude equal to 460 m [30]. This situation gives the city of Marrakech to be classified in the fifth climatic zone [31]. Winters in Marrakech are often cold at night and in the morning. Summers are often torrid, with average temperatures of 28 °C. During the day, the temperature may exceed the 40 °C threshold. Table III will show some meteorological properties of the two selected areas in the test period «July 15». Therefore, for these climatic conditions, a large part of energy consumption is devoted solely to air conditioning to ensure thermal comfort for the inhabitants.

TABLE III
Casablanca and Marrakech Meteorological Data

Zone	$T_{a,min}$	$T_{a,max}$	RH	FF
Marrakesh	17.9	45.0	36	2.7
Casablanca	18.6	33.4	80	2.5

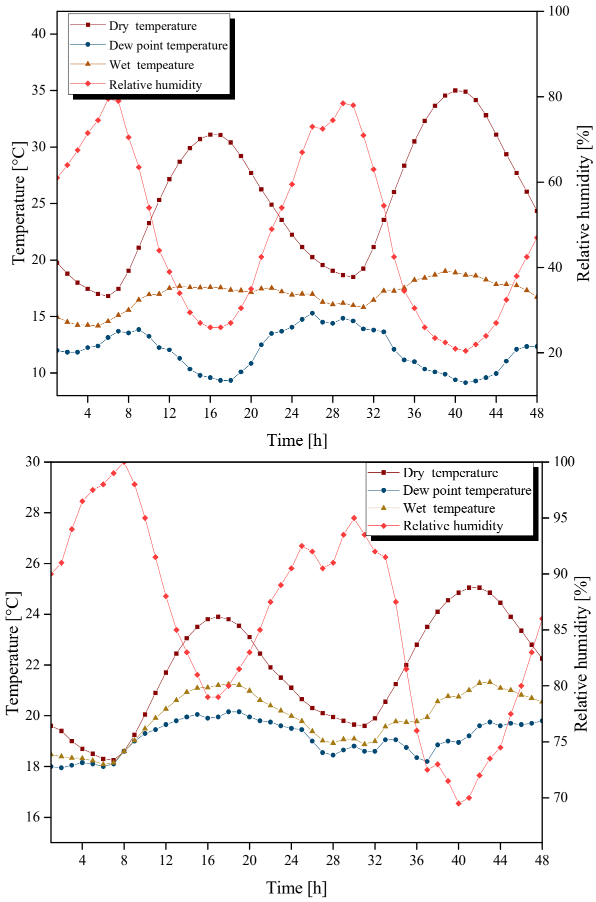


Fig. 4 Casablanca and Marrakech meteorological data [33]

V. Numerical Modelling

By TRNSYS, we carried out a numerical study to determine the influence of the climatic properties of the selected areas on the cooling power produced by night radiation. In fact, we began by studying the variation of the ambient temperature, the sky and the panel respectively over 48 hours. The results obtained are used to determine the variation of cooling power in the same time interval. Generally a simulated process in TRNSYS is configured by connecting components graphically in the simulation studio. Every «type» or «component» is described by a mathematical model in the TRNSYS simulation engine and has a corresponding set of preforms in the simulation studio as shown in Fig. 2. Our TRNSYS program is based essentially on three Steps that are presented on Fig. 5:

- Modelling of the environment
- Thermal sensor modelling
- Calculation of results

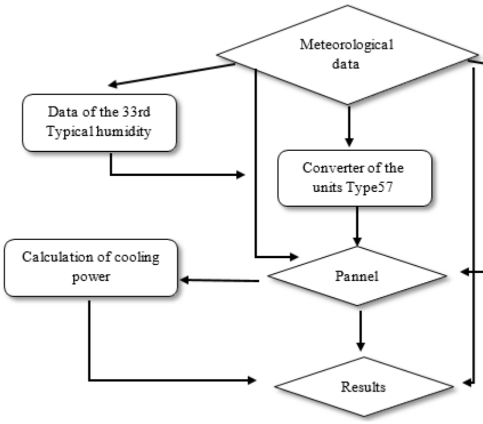


Fig. 5 Explanatory diagram of the steps of TRNSYS modelling

VI. Results and Discussions

One of the required situations for night radiation cooling is to have a sky temperature below the panel temperature. In this case, the panel seeking to achieve its thermal equilibrium of "Te (transmitter) = Tc (sky)" through the radiative and convective loss of heat to its environment. This loss is based on the thermal emission from the panel to the existing environment. The latter has stationary properties such as humidity, temperature and absorptivity of the atmosphere, which can influence panel performance. The results presented in this section are obtained in the same August period, as we have already reported in the previous section "between 14-16 July that is to say for 48 hours" for the two zones study "Marrakech and Casablanca".

A. Effect of Climatic Properties on Night Radiation Cooling Power

In this section we study the variation in the power of the night cooling by accrediting the results of Section V *A* to determine the most efficient material type and the dimensions of Section II to define the geometry of the panel. Fig. 6 represents the variation in the power of night radiation cooling as a function of time "within 48 hours of the test" in the two selected areas. According to the figures and in the range of 0-48 h, as indicated in Fig. 6, the first is the day the panel temperature will be higher than the sky temperature, so in this case, we cannot have a night cooling power "in 8:00 a.m., from 30:00 a.m., until 40:00 a.m." The second part is night, the atmosphere cools because of the absence of solar rays, which allows us to have a more important phenomenon of night radiation. In fact, we considered that in the first part the power of the night-time cooling equals 0 and we presented only the night periods, this allows us to clearly specify the power of the night radiation cooling produced. This power which is produced from the outer surface of the panel made of aluminium varied between 42.2~18.6 W/m² and 115.6~24.3 W/m² in the first night in Casablanca and Marrakech respectively, and in the second night the power creates a variation from 40.2 W/m² to 17.25 W/m² in Casablanca and from 96.25 W/m² to 32.21 W/m² in Marrakech. These results show us that the usefulness of this technique will be very important in Marrakech, which is characterized by a warm and dry climate.

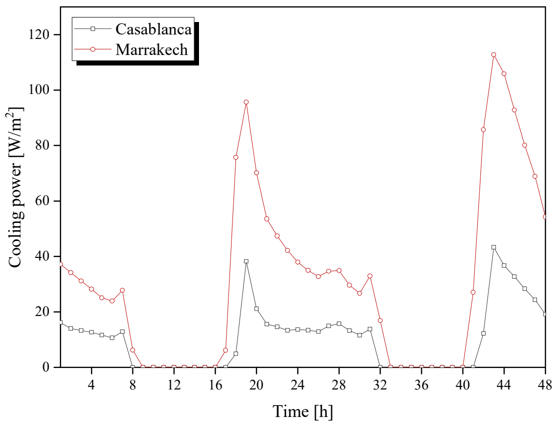


Fig. 6 Cooling power in Marrakech and Casablanca

B. Material Improvement

Essentially in the interval we have chosen [0-48 h], there are two periods where the cooling power can take place respectively, from 1 am to 6 am and from 20 h to 30 h. But, in [6h-20h] and [30h-46h] we cannot have that power, because the high intensity of solar rays. Indeed, the panel temperature will be higher than the sky temperature; one cannot have a cooling effect on the outer surface of the panel.

From 00:00 h until sunrise on the first day, the temperature of the outer surface, respectively, based on white aluminium-granite and aluminum, recedes at an average of 17.2 °C and 16.8 °C respectively, to create a 2.5 °C deviation from the ambient temperature.

For the second night and when we arrive at 18:00, the panel temperature starts to decrease in parallel with the ambient temperature, to giving a difference of 4 °C, this value will decrease to be 2 °C at the end of the night. The two panels "aluminum and aluminum plus a thin layer of white granite" have the same temperature variation in the night, but during the day the temperature of the panel made of aluminum takes higher values than the temperature of the panel which has a layer of white granite. These results show that the same performance can be achieved during the night of the aluminium-based panel, which is the most used in night-time cooling technology… with the same panel but by adding a thin layer of white granite to increase reflectivity during the day, which allows us to validate the study that we did previously [32] on the performance of white granite use it as a thin layer add to the outer surface of hybrid panels for night cooling.

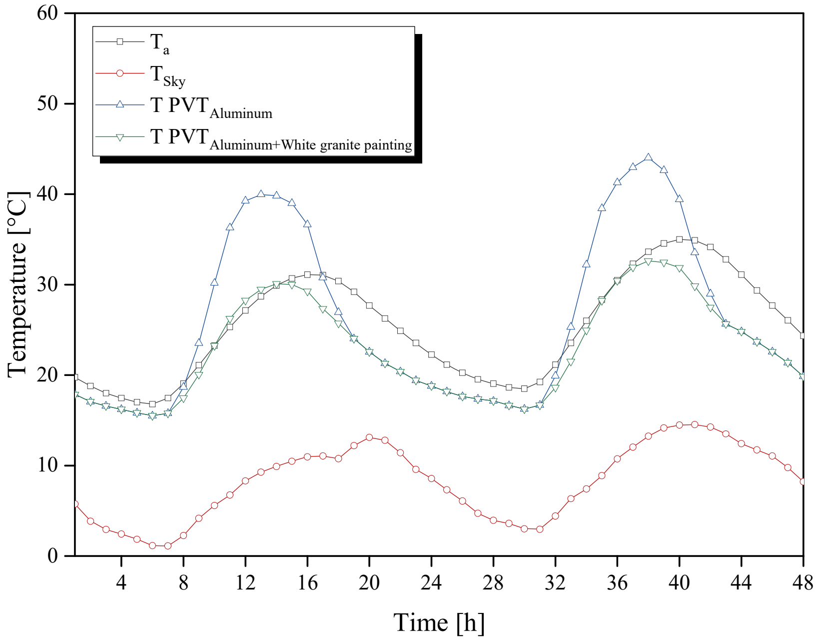


Fig 7 Ambient Temperatures, Transmitter and Heaven Variation by Time in Marrakesh

VII. Conclusion

The program carried out with the TRNSYS tool, allowed us to determine the influence of climatic properties on the variation of the temperature of the hybrid panel. The recorded temperature change associated with a power change. Power varied between 115.6~24.3 W/m² marked in Casablanca, to be the most suitable area to practice night cooling by night radiation. The comparative study of the two materials using temperature variation within 48 hours allows us to determine the most efficient materials. These results show that one can have the same performance during the night of the aluminum-based panel, which is most used in night-time cooling with the same panel but adding a thin layer of white granite to increase reflectivity during the day, which allows us to validate the study we have done previously [32] on the performance of white granite regarding the use as a thin layer add to the outer surface in hybrid panels for night cooling.

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