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Research Paper

The effect of cool paints and surface properties of the facade on the thermal and energy efficiency of buildings in a hot and arid climate

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A B S T R A C T

The facade of a building is a decisive factor in the thermal and energy performance of buildings. Its surfaces are considered as zones of heat transfer between the inside and the outside. Surface properties, especially color and texture; which have an important role on solar absorption and thermal emittance of the facade and subsequently the thermal operation of the building. The purpose of this article is to study the impact of surface properties of the facade on the thermal comfort and energy efficiency of buildings in a hot and arid climate. The investigation is based on an experimental approach by taking measurements in test cells with an insulating paint (with nanoparticles) as well as on a numerical study by the dynamic thermal simulation software TRNSYS. Several parameters were studied such as ambient temperature, internal and external surface temperature and energy consumption. The results showed that the surfaces of the facade represent with excellence the place of heat exchange between interior and exterior whose surface properties have a colossal impact on the thermal and energy operation of the building. The insulating paint with its nanoparticles has a considerable impact on the reduction of temperature. The proper choice of material absorption has a great influence on the reduction of temperatures and energy requirements of the building.

1 Introduction

The rationalization of the energy waste has become a universal issue in all sectors. The building sector is considered as one of the most energy-intensive sectors worldwide [1-3] with a percentage of 40 % of total primary energy consumption [4]. This large quantity is exploited mainly to improve the thermal situation of the occupants [5, 6] through the use of great ingenuity and the integration of a large number of equipment [7, 8] which makes the reduction of this quantity a great challenge [9].

In Algeria, the energy consumption of the building sector represents a percentage of 41 % of the final consumption [10] as shown in Fig. 1. Buildings are particularly large consumers of energy due to the uncontrollable exploitation of heating and

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cooling. The negligence of the parameters of thermal environment and the climatic specificities of the context during the design generates an uncomfortable building, which features a considerable energy consumption.

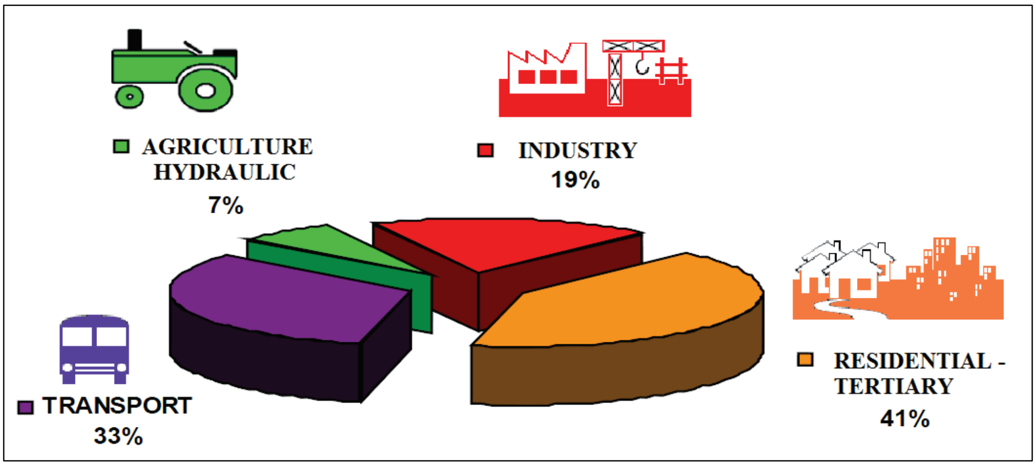

Fig. 1 – Algeria's final energy consumption by sector [10]

The indoor thermal environment is influenced by several parameters that affect the energy performance of the building such as materials and opaque surfaces [11]. Hence, the need to find efficient means to minimize energy consumption [12].

The exposed facade to solar radiation generates phenomena of absorption and reflection that vary according to the surface characteristics of materials [13]. The color (light or dark) is a surface property that influences several parameters such as the amount of radiation absorbed and reflected, the surface and ambient temperature, the heat gains and thereafter the thermal and energy performance of the building [14,15]. The texture of a surface (smooth or rough) is another important surface property that affects the absorption and reflection of solar radiation [13]. It turns out that there are properties that allow us to control the surface temperature.

Several researches have been a part of an effort to optimize the thermal operation and energy efficiency of the facade's elements given its role. This improvement can be established at several levels through the exploitation of different methods [16, 17]. A great deal of passive strategies are considered as good solutions to optimize the energy performance of buildings while improving the internal thermal environment [4, 12], particularly at the level of the envelope [18] through the use of reflective facades that minimize surface temperature and heat gain, improve thermal comfort and reduce energy requirements [19]. Cool materials with a clear color have a great potential to reduce the surface temperature compared to other dark colored materials [11]. In fact, there are no universal solutions recommended [20], which requires in-depth research on the impact of surface characteristics of materials in different climates.

Many researchers consider cool materials as an effective solution to prevent heat accumulation on the surface of the facade and reduce the amount of heat-transferred inwards [21]. These materials can reduce the surface temperature down to 15 °C [22]. They are characterized by a very high values of solar reflectance and infrared emittance, which are the two main parameters in order to control the surface temperature of an element [19, 23-25].

According to the authors' knowledge, there are no studies done on the impact of surface properties of the facade in Algeria and particularly in hot and arid areas where we have seen a wide variety of colors and textures with a negligence of thermal and energetic side.

The objective of this research is to study the impact of surface properties of the facade on the thermal comfort and energy efficiency of buildings in a hot and arid climatic context. The parameters studied are color, texture and their absorption using dynamic thermal simulation as a study tool. The impact of the cool paint with nanoparticles (having a high solar reflectance and a high thermal emittance) was studied through experimental work on test cells.

2 Materials and methods

2.1 The study context

The context of the study focuses on hot and arid areas taking the city of Biskra as a case study (southern Algerian city at a latitude of 34° 48' North, a longitude of 5° 44' East and an altitude 86 meters). According to weather data from the Biskra weather station, the annual average temperature is 22.5 °C with an average monthly temperature of up to 35 °C in July. Figure 2 shows the monthly radiation for the city of Biskra for one year generated by "Meteororm V.7.2.1" meteorological data software [26].

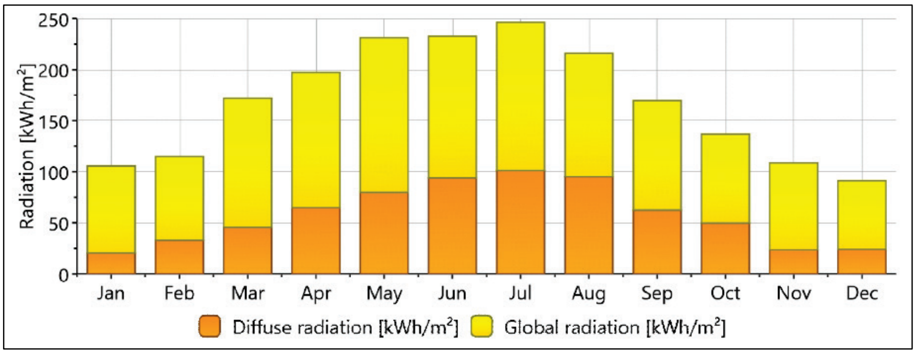

Fig. 2 – The monthly radiation of the city of Biskra during one year [26]

We noticed that the radiation values are high throughout the year especially during the summer. This season is characterized by high values of direct and diffused radiations with a global radiation of nearly 250 KWh/m² in July, which influences the surfaces of the facades. This solar energy greatly affects the indoor environment and the energy needs of the building [27] which requires finding an adequate solution at the level of the facade surface to minimize the negative effects of solar radiation.

2.2 The presentation of test cells

The properties of the envelope materials have a crucial role in the thermal operation of the building [28], such as the use of cool paints that reduce the load on cooling [28]. In this sense, several researches have been made through the use of cool materials [4,30] using test cells for the study such as the works of [30-36].

In our case, two test cells were made in order to study the impact of solar reflectance and the thermal emittance of the surface of the facades on the external and internal surface temperatures, as well as the ambient temperature using cool (insulating) paint with nanoparticles.

The Figure 3 illustrates the two test cells realized with a rectangular shape (80x90 cm) and a height of (90 cm). The walls are hollow bricks of (10 cm) with a cement coating of (1 cm), a screed of (2 cm) and a solid slab of (7 cm).

Fig. 3 – The two studied test cells

The first cell (C1) was used as a reference cell (control). The second (C2) was covered by an insulating (cool) paint with nanoparticles (having a high solar reflection and a very high thermal emittance) to test the impact of these two parameters on the thermal behavior of the facade.

The used insulating paint contains nanoparticles (20 µm micrometer semi-hollow silica micro-beads, titanium oxide, water and acrylic silicone) according to the technical sheet of the painting as shown in Fig. 4.

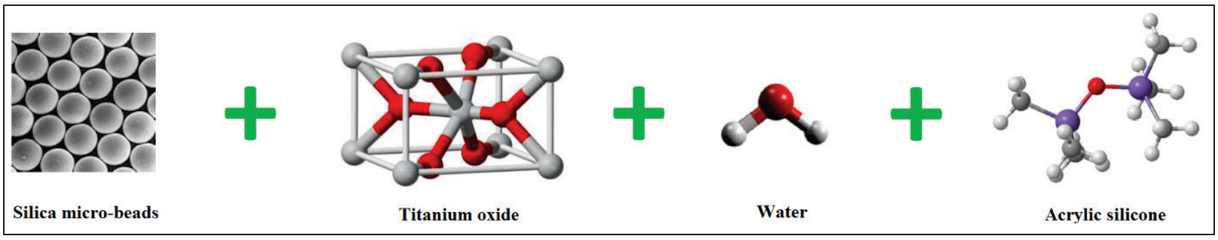

Fig. 4 – The composition of the used insulating paint

These nanoparticles give a high reflection of the visible spectrum up to 90.4 % and a value of 94.6 % of infrared, which minimizes the amount of absorbed heat and decreases the heat transfer. These cool paints produce a high infrared reflectance compared to ordinary paints of the same color with a surface temperature difference of more than 10 °C [37]. According to a research by Hernández-Pérez [11], cold colors are able to reduce the surface temperature down from 5 to 13 °C compared to the same ordinary color.

2.3 Protocol of the experimental study

Analysis of the meteorological data of the city in question has enabled us to determine the design day "typical day" of the measurement during the hot and cold period. The determination of this day was based on the calculation of the average daily temperature [38] during the studied month. This calculation was done in 15 years (between 2000 and 2015) and the typical days selected for the measurements are August 9th and December 12th of 2017.

Two-hour measurements were done from 8 h to 16 h. The parameters measured are the outdoor temperature (T_{out}) under shadow at a height of 1.2 m, the external surface temperature (T_{es}), the internal surface temperature (T_{is}) and the ambient indoor temperature (T_a).

The Figure 5 illustrates the instruments used for taking measurements (a) a "Testo 480" anemometer and (b) an infrared thermometer for measuring the surface temperature.

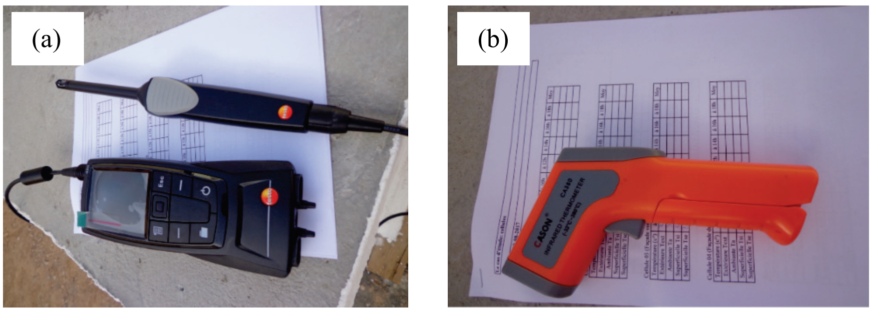

Fig. 5 – The instruments used for taking measurements

3 Numerical simulation

Numerical simulation programs are seen as powerful tools for helping to make the right choices [39], such as building envelope elements, to study building systems and optimize building operation [28, 40, 41] and their energy performance under different conditions [42].

3.1 The simulation software

The numerical study was elaborated with the software "TRNSYS" (Transient System Simulation) Version 17. This dynamic thermal simulation program [43] is addressed to the actors of the building [41], it is mostly used by the researchers given its advantages. The geometry of the model was created using the "SketchUp" program using the "Trnsys-3D" plugin. The software "Meteonorm V.7.2.1" in "Tm2" format generated the climatic file of the studied city.

3.2 The numerical model and the simulation protocol

We have created three numerical models ($M_{ab0.1}$, $M_{ab0.5}$, and $M_{ab0.75}$). The Figure 6 shows the geometry of the simulated models and the material composition of the facades.

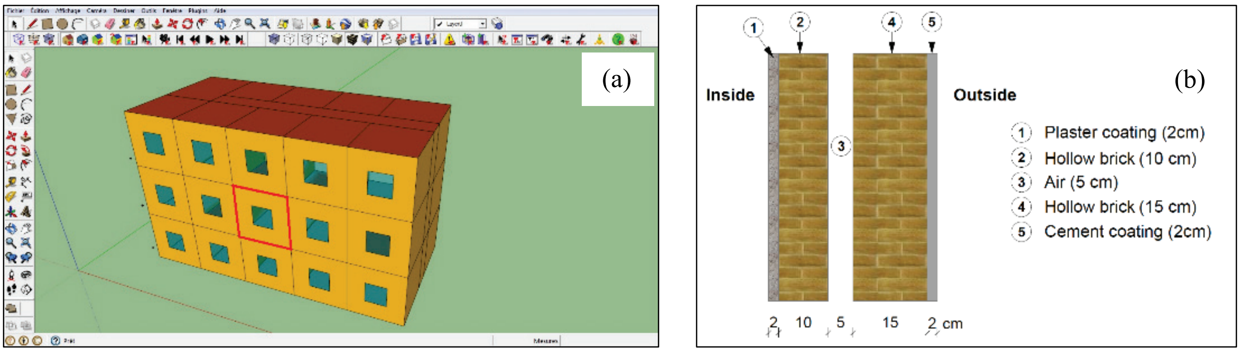

Fig. 6 – The geometry of simulated models and their material composition

The material composition of the simulated walls is similar to the composition of the used walls in this region. The Table 1 illustrates the thermal characteristics of the used materials.

Table 1 - The thermal characteristics of the materials of the simulated models

	Thermal conductivity λ (W/m.k)	Specific heat C (KJ/kg.k)	Density D (Kg/m3)	Thickness (cm)
Hollow brick	0,48	1080	900	10-15
Plaster coating	0,35	936	1150	02
Cement coating	1,40	1080	2200	02
Air	0,047	1000	1	05
Reinforced concrete	1,75	1080	2500	10
Hollow-core slab	1,20	1000	1300	16

These three models are similar only in terms of exterior surface properties of facades with low, average and high absorption. Table 2 demonstrates the characteristics of the models.

Table 2 - The surface properties of the simulated models and their absorption coefficients

Model	surface properties	Absorption
$M_{ab0.1}$	Smooth surface and light color	0,1
$M_{ab0.5}$	Smooth surface and average color	0,5
$M_{ab0.75}$	Rough surface and dark color	0,75

Detailed scenarios that affect all parameters were introduced (infiltration, internal gains, equipment, number of people and their activities). To estimate energy requirements, a temperature threshold was determined for the functioning of the equipment (20 °C for heating and 25 °C for cooling). In the aim of avoiding the errors of the initialization of the simulation, the period of the simulation was chosen during one year. The results were exported in (xls) format. The graphs were demonstrated by the "OriginLab" software by choosing extremely hot and cold conditions (3 days in each season).

3.3 The mathematical model

The "type 56" is used for numerical simulation by taking into account different thermal factors as shown in Fig. 7.

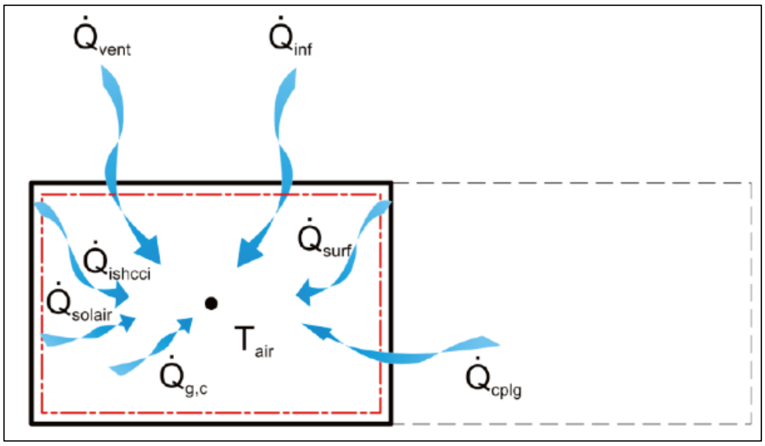

Fig. 7 –The different thermal factors [44]

The details of the mathematical models of convective heat flux in the air node are defined in "type 56" of the TRNSYS software [44] by the following equation:

$$Q_i = Q_{surf,i} + Q_{inf,i} + Q_{vent,i} + Q_{g,c,i} + Q_{cp\ lg,i} + Q_{solair,i} + Q_{ISHCCI,i} \tag{1}$$

Where:

$Q_{surf,i}$: is the convective gain from surfaces.

$Q_{inf,i}$: is the infiltration gains (air flow from outside only).

$Q_{vent,i}$: is the ventilation gains.

$Q_{g,c,i}$: is the internal convective gains (by people, equipment, illumination, radiators, etc.).

$Q_{cp\ lg,i}$: is the gains due to (connective) air flow from airnode (I) or boundary condition.

$Q_{solair,i}$: the fraction of solar radiation entering an airnode through external windows.

$Q_{ISHCCI,i}$: is the absorbed solar radiation on all internal shading devices of zone and directly transferred as a convective gain to the internal air.

4 Results and discussion

4.1 Experimental results

The temperatures recorded during the design day of the summer period (August 9th, 2017) in both cells are shown in Fig. 8. The graph (a) illustrates the external surface temperature (T_{es}) and the graph (b) shown the internal surface temperature internally (T_{is}) in both cells.

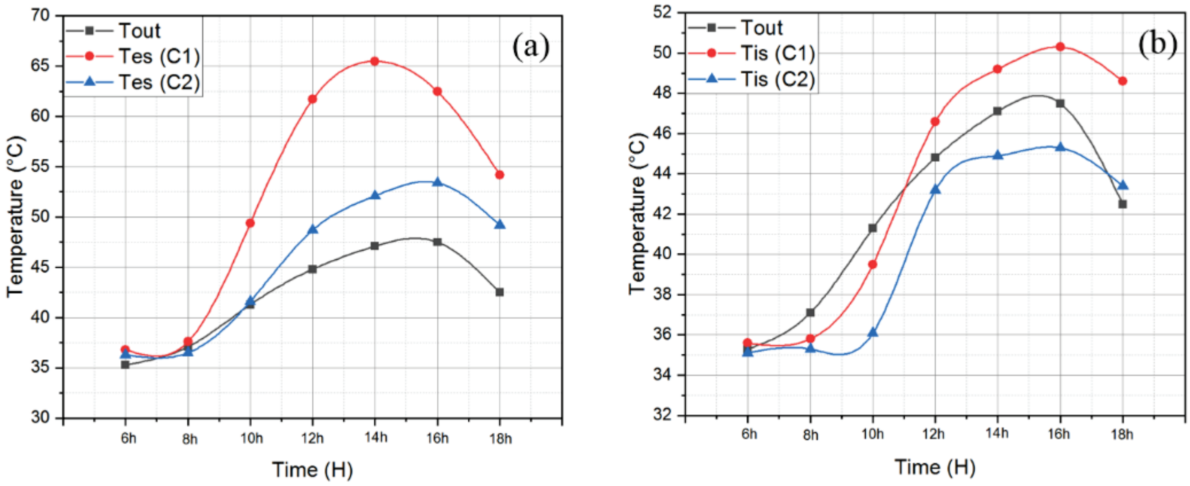

Fig. 8 – Graphs of surface temperature measured during the design day (August 9th, 2017)

In graph (a), it is clear that the values of the external surface temperatures exceed the values of the outside temperatures from 8 h, given the influence of solar radiation. We notice that the (T_{es}) of the cell (C2) are very low compared to the temperatures of (C1), with a maximum difference of 13.4 °C at 14 h given the positive impact of the nanoparticles of the insulating paint (the great solar reflectance and high thermal emittance) which allows to reduce (T_{es}) down to 20.45 %. This reduction affects directly the internal surface temperatures (T_{is}).

Concerning the graph (b), we notice that the internal surface temperature of (C1) has increased from 10 h and exceeds (T_{out}) at 11 h under the influence of the large solar radiation absorbed by the walls. On the other hand, in the cell (C2), the (T_{is}) is lower than (T_{is}-C1 and T_{out}) during the whole day with a maximum difference of 5 °C at 16 h between (T_{is}-C1 and T_{is}-C2) and a percentage of 9.94 %. The values of (T_{es}) and (T_{is}) influence directly the ambient temperature (T_a).

The Figure 9 shows the graph of ambient temperatures measured during the design day of the summer period.

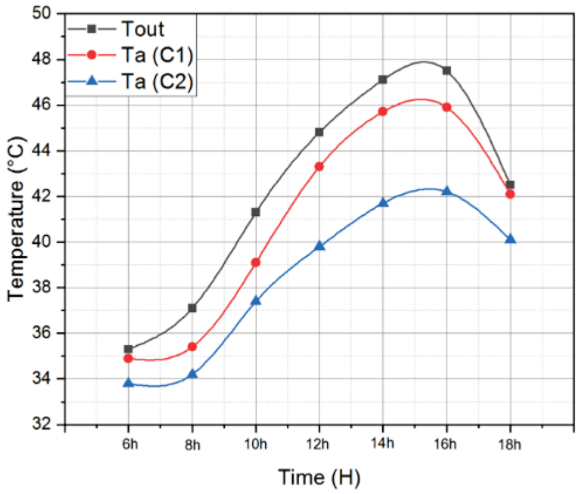

Fig. 9 – Graph of ambient temperatures measured during the design day (August 9th, 2017)

It is found that the outside temperature is very high especially after 8 h with a maximum value of 47.5 °C to 16h. Concerning the ambient temperature, we notice that the (T_a-C2) is lower than (T_a-C1) during the whole measurement period with a fall down to 4 °C at 14 h under the influence of the great thermal emittance of the insulating paint that confirms its importance on lowering temperatures.

The Figure 10 shows the temperatures measured during the design day of the winter period (December 12th, 2017) in both cells. The graph (a) demonstrates the (T_{se}) and (b) the (T_{si}).

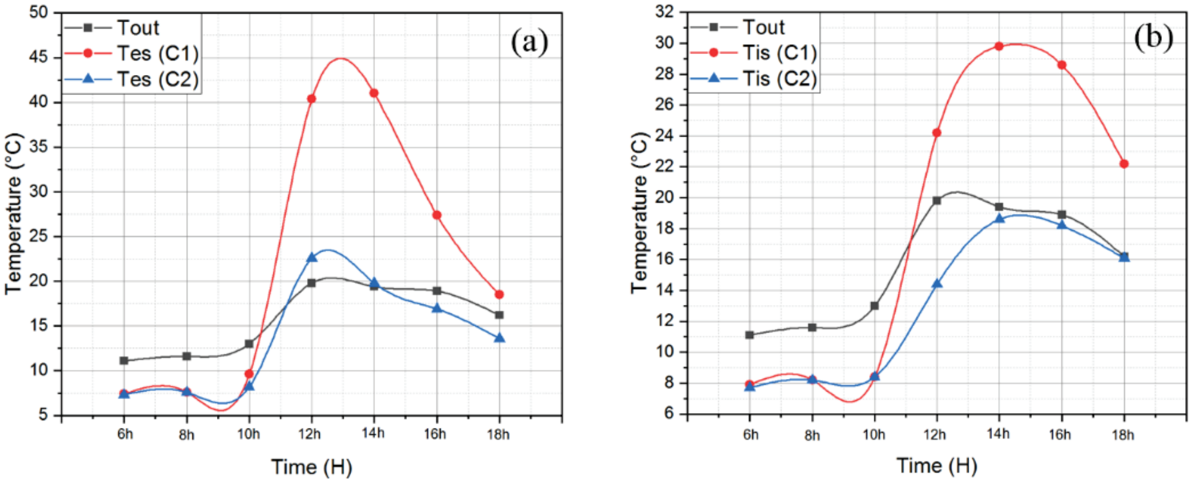

Fig. 10 – Graphs of surface temperature measured during the typical day (December 12th, 2017)

The graph (a) of the (T_{es}) reveals that (T_{es}-C1) is high even in winter where we recorded a maximum value of 41°C at 14h. On the other hand, the surface properties of (C2) decrease (T_{es}) with a difference of 21.2 °C and a large reduction with the percentage of 51.7 %. Thermal emittance has a great impact on the reduction of external surface temperatures.

At the level of the graph of the internal surface temperature (b), we see that there is a considerable increase in the curve of (T_{is}-C1) after 11 h, which is generated by the large amount of heat absorbed by the external surface given its characteristics (solar reflectance and low thermal emittance). The maximum difference marked is 11.2 °C at 14 h (a percentage of 37.58 %).

The ambient temperature graph measured during the design day of the summer period is shown in Fig. 11.

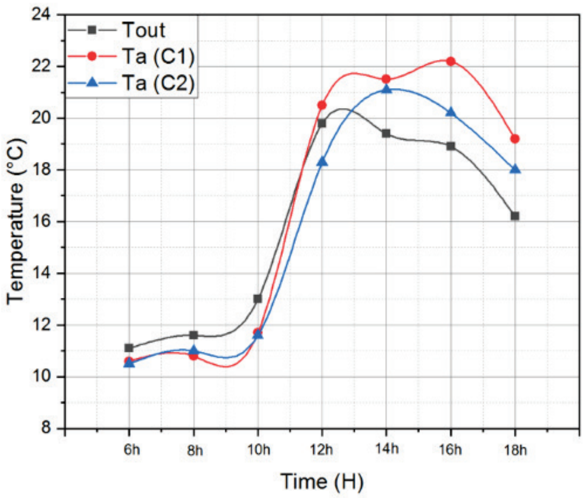

Fig. 11 – Graph of ambient temperatures measured during the design day (December 12th, 2017)

The ambient temperature curves reveal that the two cells have almost similar thermal behavior from 6 to 10 h. From 10h onwards, we notice the increase of the curve of (T_a-C1) in a large manner characterized by variations with a maximum temperature of 22.2 °C at 16 h. On the other hand, the curve of (T_a-C2) is characterized by a homogeneous operation without great variations. The surface properties of (C2) have allowed us to avoid the large increase in (T_a) generated by solar radiation that can produce uncomfortable situations even in winter (in a hot and arid climate).

Overall, (C2) has a good thermal behavior compared to the reference (C1). The insulating paint with its nanoparticles has shown its reliability in a hot and arid climate. The great solar reflection and the high thermal emittance have advantages in winter and especially in summer. During the summer, these two parameters have a huge impact on reducing the (T_{es}) of the facades surfaces, which in turn minimizes the amount of transferred heat inward while reducing the (T_{is}) of the wall and eventually avoid the increase of the (T_a). During the winter, they allowed us to benefit from heat gains while avoiding the surplus heat.

These points are confirmed by other researches on the influences of cool-colored coatings (have a high solar reflectivity and a high thermal emissivity) where they have impacts on the lowering of the surface temperature which will influence the improvement of conditions of internal thermal comfort; while reducing the energy consumption of cooling [11,19,23,24].

These results allowed us to discover the impacts of surface properties (solar reflectance and thermal emittance) on the thermal behavior of facade surfaces as well as the ambient temperature in a hot and arid climate.

4.2 Validation and results of the simulation

The TRNSYS software has shown its performance and has been validated several times [41, 45]. The validation of a numerical model requires a correspondence and coherence between the simulated and measured values [8, 45] with a difference not exceeding 10 % [46-48].

In our case, we compared an identical control model to an existing one. The results of the simulation were compared with the measurements made in this building in order to validate the numerical model. This comparison is shown in Fig. 12. First, we checked the temperatures of the meteorological file because of its impact on the results of the simulation. Reading the two outdoor temperature curves ($T_{out\_}$ measured and $T_{out\_}$ simulated) has permitted us to see the existence of a correspondence between the simulated and measured temperature with a difference of 1.6 °C up to 2.9 °C with a percentage of 4.01 % to 6.69 %; these values are less than 10 % therefore the climatic file is correct.

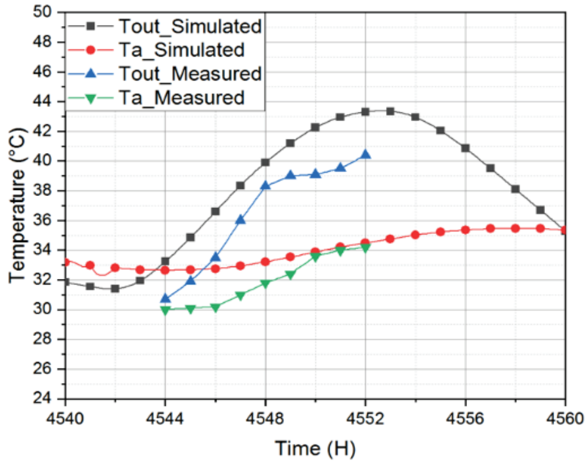

Fig. 12 – Comparison of measured and simulated temperature graphs

As regards to the two ambient temperatures ($T_{a\_}$ measured and $T_{a\_}$ simulated), it can be seen that the two curves are consistent with a difference of 0.2 °C to 2.65 °C and a percentage of 0.58 % to 8.11 %. These percentages are less than 10 % hence our numerical model is validated.

The difference between the numerical and experimental results is the cause of a gap between the actual measured temperature values and the climatic file values; which has a direct influence on the ambient temperature. The most important element is the existence of the coherence between the measured and simulated curves with a difference of less than 10 %, which validates the realized numerical model.

The Figure 13 illustrates simulated external surface temperatures for three days of winter (a) and of summer (b).

We notice that each increase in the absorption of the surface of the facade (dark color and a rough texture) causes an increase in the external surface temperature. This increase can reach up to 19.3 °C with a percentage of 57.44 % in winter and 8 °C (15.65 %) in summer between the two models ($M_{ab0.1}$ and $M_{ab0.75}$).

The values of external surface temperatures (T_{es}) confirm the importance of the proper choice of the color and the texture of the facades given their large impacts on the absorption of surfaces and subsequently the amount of heat stored in the envelope.

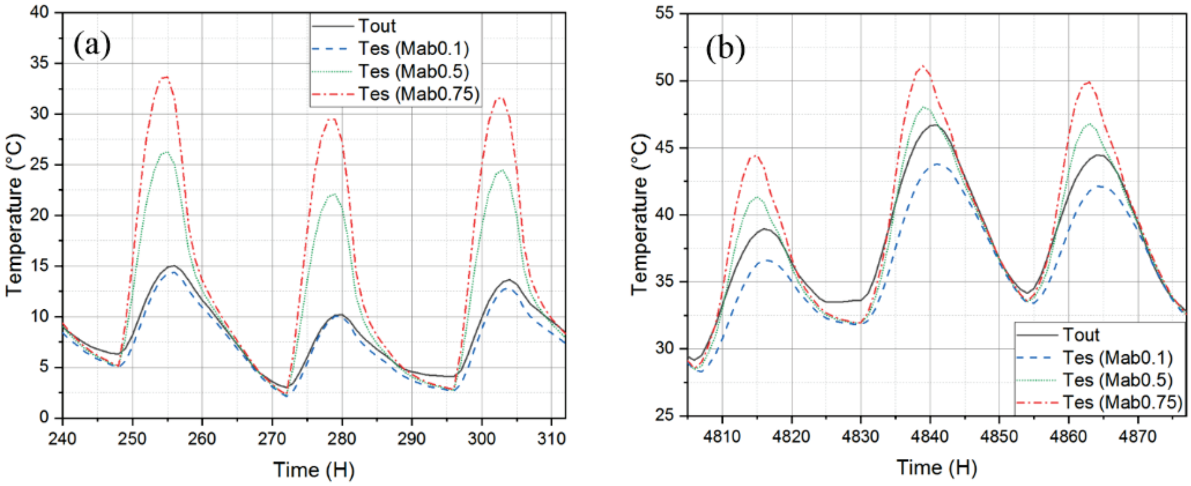

Fig. 13 – Simulated external surface temperature graphs

The increase of the values of the surface absorption influences the (T_{es}) and later on the (T_{is}). The simulated internal surface temperatures over three winter days (a) and three summer days (b) are shown in Fig. 14.

We notice that the influence on the (T_{is}) is less than in the (T_{es}). In winter, in graph (a) the difference recorded between the two models ($M_{ab0.1}$ and $M_{ab0.75}$) is 12.65 %. At the graph (b) in summer, the marked difference between the two models ($M_{ab0.1}$ and $M_{ab0.75}$) is 4 %.

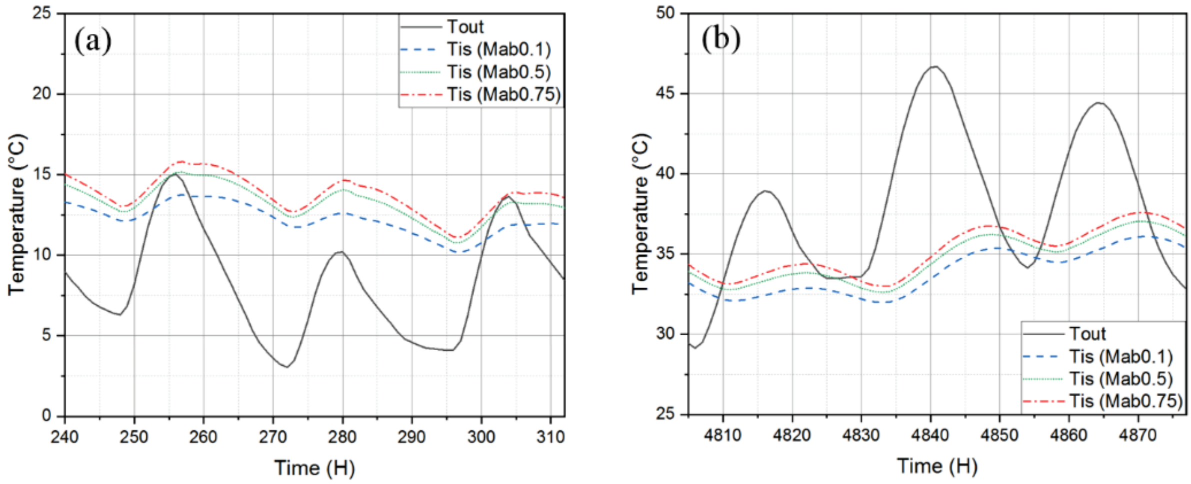

Fig. 14 – Simulated internal surface temperatures graphs

The simulated ambient temperature for one year in the three models is illustrated in Fig. 15.

Overall, we note that the ambient temperature of the model ($M_{ab0.75}$) is very high throughout the year especially during the warm period, which explains the role of the great absorption of surfaces on the increase of ambient temperature. Contrariwise, the ambient temperature of the model ($M_{ab0.1}$) is very low throughout the year compared to the first model given the low absorption of its surfaces. The reduction in surface absorption (from $M_{ab0.75}$ to $M_{ab0.1}$) has allowed us to minimize the ambient temperature down 3.18 % in summer.

The low absorption surfaces (light color and smooth texture) affect the thermal operation of the envelope in a big way. Through the reduction of absorbed solar energy we can avoid the accumulation of heat in both surfaces of the facade which optimizes the thermal environment while reducing energy requirements [13, 27, 37].

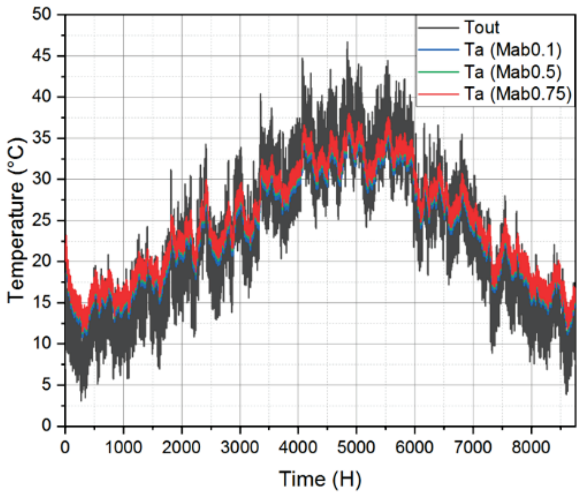

Fig. 15 – Simulated ambient temperature graph for one year

The energy requirements to ensure a thermal environment between 20 and 25 °C are shown in Fig. 16.

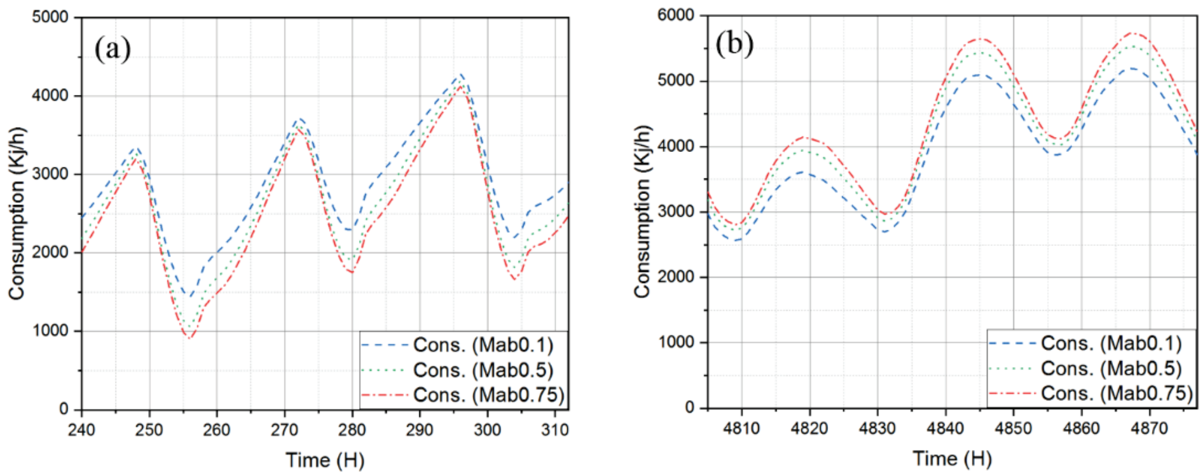

Fig. 16 – Graphs of energy needs during three days of winter and summer

We notice that the increase in the absorption of facade surfaces has two contradictory impacts depending on the season. During the cold period (a), the increase in absorption (from $M_{ab0.1}$ to $M_{ab0.75}$) has enabled us to reduce heating requirements in the cold peaks by 3.86 %. During the warm period (b), this increase in absorption from (0.1) to (0.75) causes cooling loads to increase by 9.27 %. These results assert that absorption affects heating loads and cooling.

The values of the energy requirements obtained remain rather low considering the simple materials used. There are cool coatings that have a great impact on reducing energy consumption [49] such as insulating paints with high solar reflectance and high thermal emittance.

These results gave us an idea on the importance of the choice of the absorption of facade surfaces, and their major impacts on surface temperature and thermal ambiance as well as energy consumption. The specific climatic conditions of the region must be taken into consideration in order to obtain good results.

5 Conclusion

This paper presents the main results of an experimental study based on measurements on test cells as well as on a numerical simulation by the software "TRNSYS". The objective of this research is to study the impact of surface properties of the facade on the thermal comfort and energy efficiency of buildings in a hot and arid climate. The surface parameters studied are absorption (the impact of color and texture), thermal emittance, solar reflectance and their impact on surface and ambient temperatures.

The experiment asserts that the use of surfaces with high solar reflectance and high thermal emittance affects the thermal behavior of facades in a considerable way. The cool (insulating) paint with its nanoparticles has shown its reliability in a hot and arid climate through increasing the amount of reflected solar radiation, which decreases the amount of heat stored in the material. The great solar reflection and the high thermal emittance have proven in summer by reducing the external surface temperature down to 13.4 °C with a percentage of 20.45%. The latter influences the flow of heat transferred inward while reducing the internal surface temperature down to 5 °C (a percentage of 9.94 %). Subsequently, this operation decreases the ambient temperature by 4 °C with a reduction percentage of 8.75 %. The use of this paint is an appropriate solution for this type of climate.

The numerical study confirms the importance of the absorption of facade surfaces (choice of colors and textures). On the thermal level, the reduction in the absorption of the facade affects the thermal operation of the envelope depending on the season. It reduces the external surface temperature by 8 °C (15.65 %) in summer and down to 19.7 °C (57.44 %) in winter. This reduction affects the internal surface temperature of 4 % in summer and down to 12.65 % in winter. Subsequently, a reduction in ambient temperature was recorded of 3.18 % in summer and 7.04 % in winter. The latter have an impact on energy needs with a reduction of 3.86 % in winter and 9.27 % in summer.

These results explain the great impact of the surface properties of facades and their importance on the improvement of indoor thermal comfort and the reduction of energy consumption. An adequate choice of color and texture with high solar reflectance and high thermal emittance positively influences the thermal behavior and energy efficiency of buildings in a hot and arid climate.

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