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Research Article

EXPERIMENTAL INVESTIGATION OF HYGROTHERMAL BEHAVIOR OF DIRECT GREEN FACADES UNDER SEMI-ARID CLIMATE

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ABSTRACT

This paper aims to investigate the hygrothermal behavior of direct green facades and assess their efficiency under semi-arid climate. For that purpose, a comparative study was conducted in three buildings; two buildings with direct green façades (covered with deciduous climbing plants) and one with a bare façade. Air and surface temperature, relative humidity and wind speed were collected in situ and several factors were taken into consideration as thickness and density of plant cover. The analysis of measurement data revealed that direct green façades contribute to improve the outdoor and indoor thermal environment of buildings due to the effect of shading and evapotranspiration. Moreover, the different types of green façades illustrated their different heat impact on the thermal environment of buildings depending on the density and thickness of the plant layer and the covering ratio.

Keywords: green façades; hygrothermal comfort; semi-arid climate; investigation.

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1. INTRODUCTION

Cities are facing the challenges of global warming and alarming energy crisis. Precisely, in Algeria, residential and office buildings are confronted with problems of overheating and irrational consumption of electricity during overheat periods. They accounted for 42% of total final energy use [1]. So it becomes necessary to improve the building energy performance through passive cooling techniques.

It is widely admitted that one of the sustainable approaches to cooling buildings by natural means is vegetation. The relevance of its effect as a passive cooling device in the urban environment is recognized [2]. Its use to modify climate and comfort is a key design consideration in sustainable buildings [3-4].

Among the forms of vegetation in urban environment, one finds the vertical greening which became more and more useful for greening cities. As it contributes to enhance and restore the urban environment and improve buildings thermal performance [5]. Green envelopes are expected to reduce the urban heat island and energy consumption for air conditioning in buildings [6-7-8].

There are several terms for vertical greening building surfaces namely; green walls, biowalls, vertical gardens, green facades and living wall systems [9]. In this study, we were interested in direct green facades in which feature climbing plants attached directly to the wall without any supporting structure [10].

In recent years several studies were conducted in different climates considering that green façades are as a notable passive cooling technique [11], although similar studies under semi-arid climate are lacking. It is certain that plants constitute an excellent passive system for solar control of buildings offering significant advantages over conventional artificial sunscreens. Plants can provide shading effect better than blinds [12]. Plant physiology and leaf area should be considered when selecting species to maximize cooling of green walls [13].

Green facades can also enhance occupant's comfort [14] and produce changes in the ambient conditions (temperature and humidity). They can dramatically reduce the maximum temperatures of a building by shading walls from the sun and by evapotranspiration, with daily temperature fluctuation being reduced by as much as 50% [15-16-17]. Plants work as a masonry protection, making its deterioration considerably slower than walls exposed to extreme climate conditions [18].

Many studies confirm that the potential thermal benefits of vegetated walls in reducing the surface temperature of buildings facades are promising in warm and tropical climate, leading to a reduction of 74.29% in the energy cooling load [19] and decreasing the daytime average temperature by 5°C compared to a bare façade [20]. The surface temperature differences between planted and not planted dark colour walls are quite remarkable in daytime reaching 13°C [21]. Green façades temperature fluctuates between 5°C and 30°C while exposed façades heat up to 60°C and cool to 10°C [22].

Moreover, thick ivy covering a west facing wall can reduce the peak cooling by 28% [23] and increase the air humidity by 10% to 20% [24]. To take advantage of ivy-covered walls, the covering ratio should be as big as possible [25].

In Mediterranean Continental climate, differences in the indoor surface temperatures of up to about 5°C were observed between the vegetal and non vegetal enclosure [26]. It was also confirmed that an air layer located between the façade and the green screen is characterized by slightly lower temperature and higher relative humidity [27]. This air layer can produce an interesting insulating effect. But it seems necessary to take into account the renewal of the air in this space and the density of the foliage. A temperature reduction reaching up 10.8°C was obtained for green walls under the same climate [4].

This study aims to evaluate the impact of direct green facades on summer hygrothermal environment of buildings under semi-arid climate of Algeria. In order to achieve this objective, an investigation on real buildings located in Constantine city is undertaken.

2. Presentation of the case study and methodology

2.1 Constantine climate

Constantine is located in the North-East of Algeria (latitude 36’17, longitude 6°37’). It has a semi-arid climate with hot dry summers and cold moist winters. Precipitation falls reach 630mm annually. Annual mean temperatures in Constantine vary between 7.15°C and 26.8°C with an average of 16.3°C.

Bioclimatic analysis of Constantine indicates that problems of overheating occur in summer season. In this period, there is a need for an effective control of solar radiation gains, thermal inertia and night ventilation. During overheat period, from July to August, ambient temperature is high and relative humidity is low. Hence, the use of evaporative cooling systems is recommended.

2.2 Experimental methodology

The study was carried out on four storey buildings that were selected for comparison. The field experiment was conducted in three residential buildings "A", "B" and "C" (Fig.1) in which simultaneous measurements of several physical parameters were carried out during four consecutive days of July.

Fig.1. Studied residential buildings A, B and C

There are two types of green façades (A and C) and a bare façade (B) having the same construction system, the same orientation and the same surrounding environment. All tested houses have only one façade facing south west; they are made of brick (double brick masonry with an air gap in the middle) covered with plastering on the indoor side and cement on the outdoor side (Fig.2).

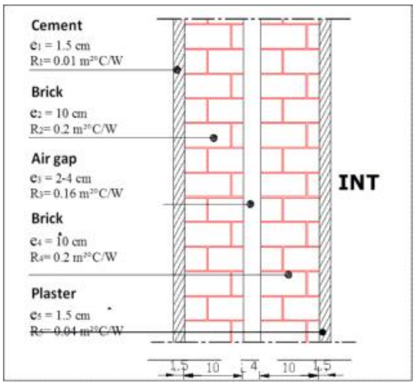

Fig.2. Detail of façade masonry

An intermediate floor is selected for all samples in order to measure the effect of green façades while eliminating the effect of the roof. The measured rooms were located at second floor level. Besides, other factors were taken into consideration to investigate the effect of climbing plants on the thermal environment of buildings as covering ratio, thickness and density of foliage.

The green screen of House “A” is very dense with a thickness of 20-30 cm and 100% of covering ratio. For house “C”, it’s less dense than “A” with a thickness of 10-15 cm and 80% of covering ratio as shown in Fig.3.

Fig.3. The three studied façades

The climbing plant covering "A" and "C" buildings is Parthenocissus quinquefolia known as Virginia creeper which is attached directly to the façade (Fig.4). It is a deciduous shrub, grown as an ornamental plant for its ability to rapidly cover walls and buildings. The leaves are composed of five leaflets joined from a central point on the leafstalk, and range from 3 to 20 cm across whose have a toothed margin.

Fig.4. Parthenocissus quinquefolia covering the building "A"

This paper focuses on the study of the hygrothermal effects of green façades on buildings. Hence, temperature, humidity and air velocity measurements were performed on the three selected buildings. All measurements of air temperature and relative humidity are carried out four days using TES Thermo-Hygrometer TES-1360A (+/- 3% R.H and +/- 0.8°C). Extech Infrared Thermometers IR400 ±4°C are used for the measurement of surface temperature. For air velocity measurements, a compact testo 425 thermal anemometer (±0.03 m/s) was used.

All these physical parameters were collected every two hours and measured simultaneously at six points at the same height. For buildings A and C, measurement points were located in the center of the test room (point1), on the internal and external surfaces of the façade (point 2 and 3), in the leaf layer (point4), at 30 cm from the plant cover (point5), and in outdoor environment (point6). For the building “B”, there are only four points 1,2,3 and 6 (see Fig.5).

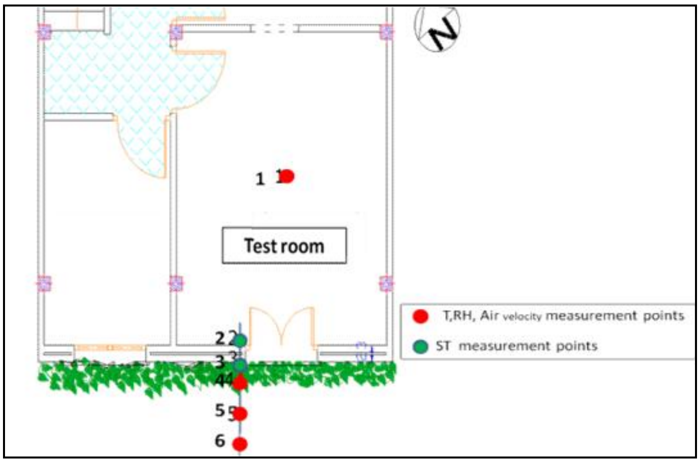

Fig.5. Measurement points

3. RESULTS AND DISCUSSION

3.1. Indoor ambient temperatures

At daytime, the variation of indoor temperatures of the three samples shows that the thermal effects of plants are quite significant. The results reveal that peak values are recorded in room “B” with a maximum ambient temperature of 33.3°C recorded at 4.pm compared to 31.1°C in room “C” and 29.3°C in room “A” at 6 pm (Fig.6). A maximum difference of 4.4°C is recorded at 4.pm between "A" and "B" and 2.3°C between “A” and “C”. This difference can be explained by the influence of direct radiation on the facade “B” and shading and evaporative cooling effects of plant covered façades. Therefore, the green screen can reduce the sensitivity of the building to outdoor fluctuations by reducing heat gains.

At this time, the room “A” recorded a maximum difference of 8.45°C at 2.pm with the meteorological temperature and 7.05°C with the microclimatic outside temperature as shown in Fig.6. Indeed, due to the local urban environment, outdoor temperatures are less than meteorological temperature at daytime and higher at night.

As a result, the interior temperatures of room “C” are higher than those of room “A” with a maximum difference of 2.3°C. The most pronounced cooling effect of green façade is observed during the middle of the day (11.am – 4.pm). Consequently, green façade “A” which has dense foliage is very effective in obstructing the sun’s rays and casting a shadow.

Nevertheless, cooling effect of green façade is significantly reduced at night. Green façades doesn’t participate in decreasing temperature. After 6.pm, the ambient temperatures decrease slowly to reach a minimum value of 28.65°C in room "B", 27.7°C in room "C" and 27.1°C in room "A". Although, room "A" recorded the lowest nighttime temperatures compared to others rooms, these values are still higher than the nocturnal outdoor temperatures. In fact all tested rooms have higher ambient air temperature compared to surrounding air temperature owing to radiation emitted by walls to the atmosphere. This negative effect can be mitigated through nocturnal ventilation [28-29].

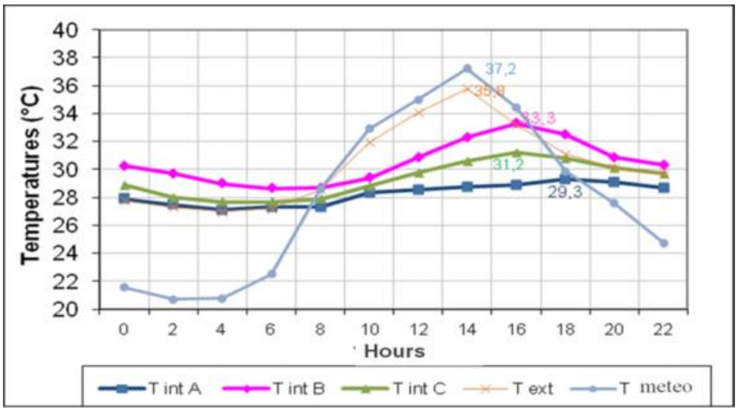

Fig.6. Variation of air temperatures in the three rooms

Fig.7 indicates that room "A" has negative values throughout the day with a maximum discrepancy of 7.05°C recorded at 2.pm which coincides with the maximum outside temperature. This explains the positive behavior of the room “A” during all the day under the effect of Virginia creeper screen; therefore, vegetation moderates temperature variations.

For the room "C", a positive discrepancy is recorded between 12.pm and 6.am due to the lack of cross ventilation (the door and shutter are closed at this time). But, from 8.am to 6.pm, the discrepancy is negative with a maximum of 5.2°C reached at 2.pm; this is explained by the protection of the wall despite its partial coverage (80%).

As for the house "B", its energy balance is rather positive between 4.pm and 8.am due to an additional energy intake which has not been evacuated because of the wall’s exposure to the direct and intense solar radiation on the one hand and the lack of cross ventilation on the other hand. Although the discrepancy of the mean indoor and outdoor temperatures is negative between 8.am and 4.pm, marking a maximum of 3.3°C at 2.pm, it remains low compared to those in houses "A" and "C".

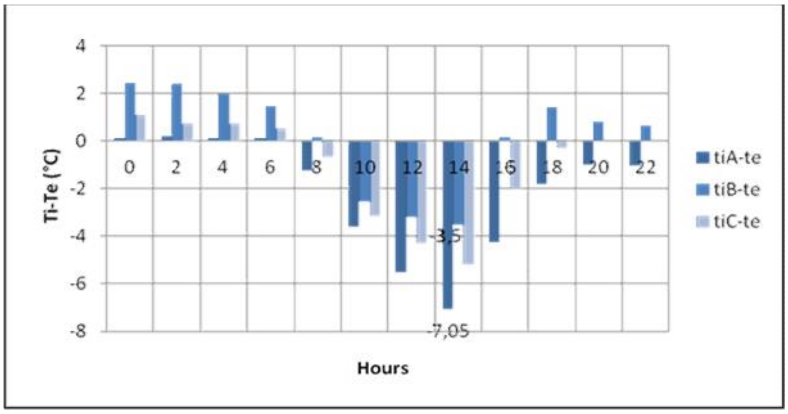

Fig.7. Variation of mean indoor and outdoor temperature difference in the three rooms

3.2. Variation of surface temperatures

Graph (a) on Fig.8 compares indoor surface temperatures measured on the three façades. It shows that the room “B” surface temperature profile varies on the same way as outdoor temperature form. The graph shows that the surface temperature of the bare façade is warmer than the surrounding. The maximum value of external surface temperature in façade “B” is 40°C whereas the maximum values in green façades (“C” and “A”) are 32°C and 29.5°C, respectively. These variations confirm the lack of effective solar protection of façade “B” and the shading effect of façades “A” and “C” provided by climbing plants and their capacity to intercept solar radiations. Consequently, the heat gain through the building envelope is reduced, and it is due to the difference of plant coverage ratio between the two façades "C" and "A".

The graph (b) on Fig.8 compares outdoor surface temperatures. It shows also the difference between the three studied rooms. The internal surface temperatures in room “B” were higher than the ambient temperature due to daily peaks caused by solar radiation absorbed through the façade. Although the internal surface temperature of this façade rises quickly at day time reaching 34.1°C at 4.pm, it falls and is close to the outdoor temperature in the late afternoon. At 6.am, the surface temperature reduced to 27°C slower than the ambient air temperature by 1.6°C. Indeed, the wall stores the daytime heat, which will be returned during the night.

The surface temperature amplitudes of the façade “A” are roughly similar to those obtained with façade “B” with a difference of 1.7°C. The green façade “A” maintain a lower surface temperature than the green façade “C” with less heat storage. This increase is mainly due to internal gains and the energy flow transmitted through the window.

As a result, the plant layer has delayed the effect of heat transfer from outside to inside. It offers a good solar protection of the building envelope by reducing conduction and radiation heat transfer.

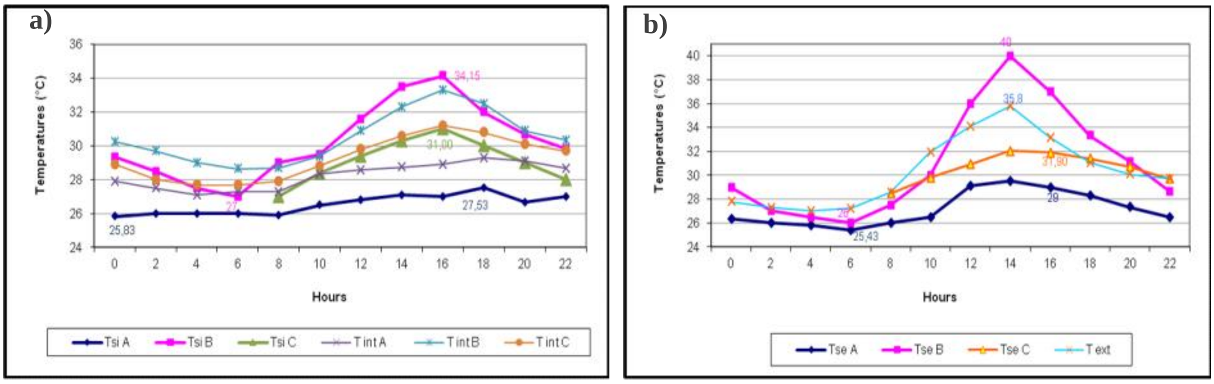

Fig.8. Variation of external surface temperatures in the three rooms

3.3 Variation of foliage temperatures

Figure 9 shows clearly that foliage temperatures and around it are lower than outside temperature. The "A" foliage temperatures range from 26.9°C to 33°C and the ones near the foliage range from 26.6°C to 34.55°C while the outside air temperatures range from 27°C to 35.8°C. For the house "C", the foliage temperatures range from 27.3°C to 33.9°C while the ones near the foliage range from 26.9°C to 34.8°C. This reduction is due especially to evapotranspiration process.

Solar radiation influences greatly plant transpiration and has a direct effect on stomata. Plants leaves open their stomata and evaporate water which will lower the leaf temperature and could decrease the air temperature near the plant. Thus, thanks to convection, the cooling is accelerated; noting that the air speed at this time is 1.39m/s.

In addition, leaf temperatures of house "A" are 2.4°C below leaf temperatures of house “C”. Consequently, leaf temperatures may be considerably influenced by thickness and density. When the foliage is dense, the evapotranspiration phenomenon is high influencing the thermal environment.

From 8.pm, the "A" foliage temperature exceeds slightly the outside temperature with a discrepancy of 0.2°C. Indeed, at night, when the outdoor temperature is relatively low, the building releases heat by long wave radiation and convection with the surrounding air [23].

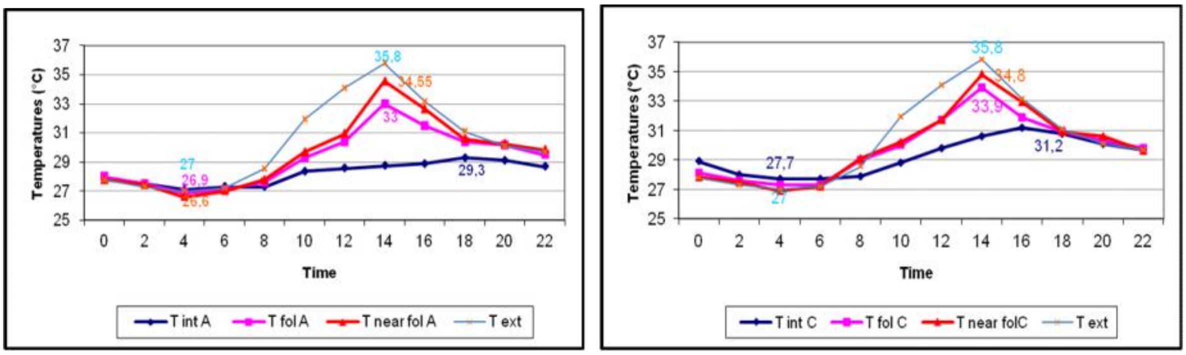

Fig.9. Variation of foliage temperatures of green façades “A” and “C”

The Fig.10 shows the thermal behavior of the three rooms at different measuring points. It should be noted that at 2.pm, while the outside air temperature registers its maximum value of 35.8°C, the temperature near the foliage of house "A" is 34.55°C, marking a difference of 1.25°C and the leaf temperature is 33°C with a discrepancy of 2.8°C. At the same time, the house "C" foliage temperature recorded 33.9°C and near the foliage is 34.8°C.

All these fluctuations can be explained by the different heat transfer processes between the leaf layer, wall and environment detailed by [23]. During the day, part of the solar radiation reaches the leaf layer and another part is reflected by the leaves, while the rest is absorbed by the wall. The leaves absorb a large amount of incident solar radiation for photosynthesis and transpiration. Due to convection and evaporation, leaf temperatures are lower than surface temperatures of bare façade. The air temperatures are gradually reduced by the green layer effect through the evapotranspiration process. The heat energy is absorbed during the water evaporation from plants, which extracts the excess heat from the surroundings. Therefore, evapotranspiration leads to a thermal gradient between the ambient air and the plant layer.

A temperature difference of 6.3°C is recorded between the external surface of wall "A" and the outside air. This is mainly due to the plant shading projected on the wall. The green screen reduces the heat transfer from the outside to the inside and therefore contributes to the reduction of the surface temperature of the wall and that of the ambient air. The gains generated inside room "A" are then limited to the internal gains. Therefore, at daytime, plant shading reduces heat gain into the building envelope by reducing the surface temperatures and by converting solar radiation to a latent heat [30-31].

By comparing these values with those recorded in room "C", this clearly shows that this room is less protected than room "A" and shows that the density, thickness and covering ratio play a major role in improving the thermal comfort of buildings. More the foliage is thick and dense; more temperatures are lower. The total absence of shading of the façade “B” promote the absorption of solar radiation during the day; which causes a rise in the external surface temperature up to 40°C while façades “A” and “C”, which reach 29.5°C and 32°C respectively. Therefore, in summer period, the leaf layer reduces the temperature of the surrounding environment and provides a thermal comfort for buildings, protecting them from extreme heat.

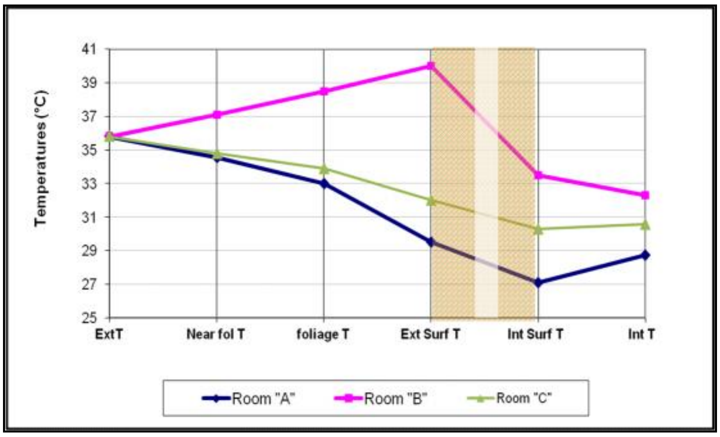

Fig.10. Temperatures evolution in the three rooms for differing measuring points at maximum outdoor temperature

3.4 Variation of relative humidity

As shown in Fig.11 and Fig.12, the humidity foliage levels are consistently higher despite the remarkable reduction found in the leaf temperatures.

These high values of relative humidity of the foliage directly affect that of the indoor air.

The ambient humidity level in room "A" is significantly higher than that of room "B" ranging from 46.3% to 61% with a maximum difference of 22.7% recorded at 4.am and a minimum difference of 7.53% at 4.pm. It exceeds outdoor humidity readings with a maximum difference of 28.4%. This observation could have two origins. The first is plant transpiration, which tends to increase relative humidity in the air near the foliage. The second is the drop in temperature, which implies an increase in relative humidity, particularly for indoor air. Consequently, an air gap between the building and the plant layer is recommended to reduce humidity storage and to allow air circulation.

In addition, the vapor exchange surface between plants and air is related to plant density and the thickness and surface of leaves. More these parameters are large; great will be the evapotranspiration phenomenon [32].

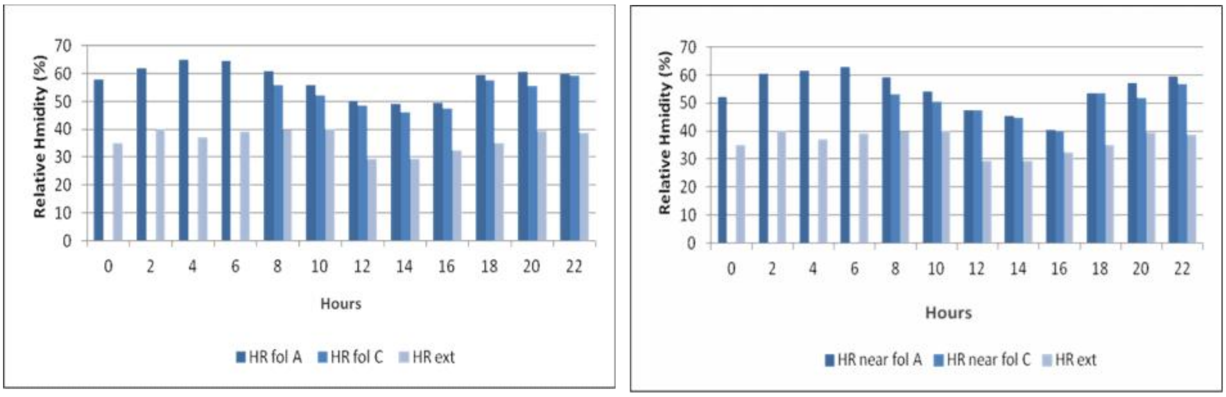

Fig.11. Variation of foliage humidity of green façades “A” and “C”

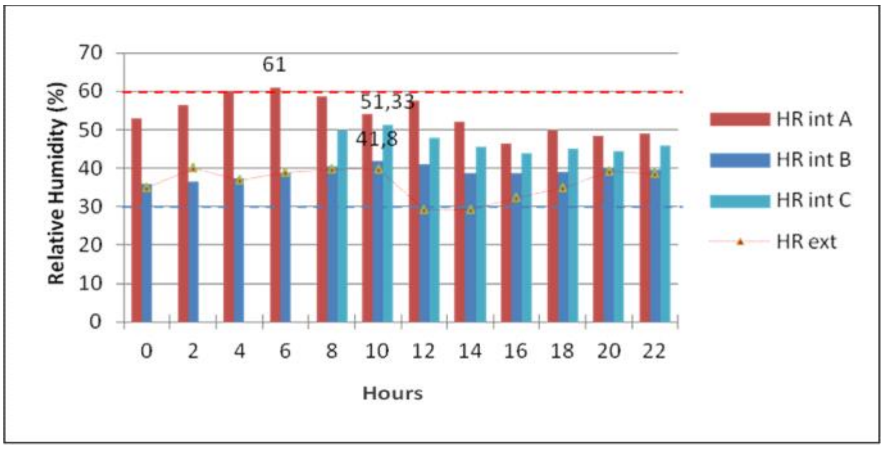

Fig.12. Variation of indoor relative humidity in the three rooms

4. CONCLUSION

This study focuses on an experimental investigation of the impact of green facades on hygrothermal environment of residential buildings under semi-arid climatic conditions during summer.

The analysis of measurement data indicates that direct green façades can be considered as a passive technique to control solar radiation under semi arid climate. Green façades can greatly affect the thermal comfort of occupants by protecting the building envelope from overheating. It acts as a buffer zone between the indoor and outdoor environment. Indeed, like a second skin, deciduous climbing plants on the southwestern side provided good sun protection of the building envelope by reducing conduction and radiation heat transfer. Climbers reduce the ambient and surface temperatures along building façades especially at daytime via shading and evapotranspiration.

Nevertheless, Virginia creeper screen contribute to increase the humidity level requiring nocturnal ventilation. Accordingly, an air gap between the building and the green screen is recommended to avoid condensation and allow air circulation.

On the other hand, the different types of green façades illustrated their different heat impact on the thermal environment of buildings. Therefore, plant density, foliage thickness and covering ratio have a high influence on the thermal environment. More these parameters are large; great will be the thermal performance of building envelope.

5. ACKNOWLEDGEMENTS

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