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ASSESSMENT OF THE ENERGY EFFICIENCY OF AN EXTERNALLY-INSULATED REHABILITATED BUILDING UNDER SEMI-ARID CLIMATE

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ABSTRACT

The current evolution of the world warrants the rethinking of the modes of construction. Improvements to insulation materials will have a large impact in the building and construction sector. The aim of this work is to conduct a modelling study using the TRNSYS 17 software to evaluate the impact of the use of different types of thermal insulators and their location on the energy consumption of buildings. The results of the simulation show that the use of a super-insulating 2-cm-aerogel, an 8-cm ecological sheep wool sheet, and an 8-cm polyurethane sheet combined with a 5-cm air layer on the outer façade of the wall, allow respectively energy savings of 18.46%, 2.32%, and 1.96% compared to the real-life case study. In order to optimize the thermal and energy performance of the building, this study presents several innovative alternative materials that are suitable for implementation as a skin for a building.

Keywords: external thermal insulation; natural nocturnal ventilation; super insulator (aerogel); modelling; energy consumption.

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1. INTRODUCTION

A large array of applications for scientific progress is available in the building and construction sector, especially in the area of thermal comfort and energy efficiency. In current buildings and those in the near-future, several insulation materials and solutions are used according to recommendations and norms defining their technical specifications. The thermal insulation of building plays a predominant role in policies of reduction in energy consumption. In the near future, nanotechnology may be used to manufacture high-performance thermal insulating materials. They would be high-porosity materials with small pockets of static air imprisoned in the porous volume having a smaller thermal conductivity than the conventional construction materials. There is currently a major interest in using so-called super-insulating materials, such as, among others, aerogels which exhibit high thermal performance. These aerogels can actually be used in insulating both opaque and transparent walls due to their very small thermal conductivity and optical transparency.

The location of the insulators plays a predominant role in delaying the heat transfer from the outside to the inside, or vice-versa. According to [1-3], the best thermal performance is obtained when the thermal insulators are placed on the outside (external façade) of the wall and the position of the insulator has a significant effect on the performance of the walls in terms of time lag and decrement factor. For economic considerations, the optimal insulation thickness to recommend is 5 cm and thermal insulation external to the building envelope is the most efficient solution allowing considerable gain in energy consumption [4]. The different parameters studied using the TRNSYS software to determine the impact of the building envelope on its energy requirements in the Algerian south, in Bechar and Tamanrasset, during the summer, show that roof insulation using a plaster false ceiling and a wooden false ceiling results in gains at ratios of 21.55% and 20.31% respectively, while wall insulation reduces air conditioning consumption at a ratio of 2.5 to 3%, which is negligible compared to the gains from roof insulation, making it thus one of the most economical solutions for improvement [5].

Thermal insulation of walls allows a decrease in heat transfers of 25 to 35% of the total transfers of the building and avoids condensation on the walls and within them [6]. In a non-insulated building, thermal bridges represent small losses (generally lower than 15%)

because the total losses through the walls are very high. However, when the walls are effectively insulated, the losses due to thermal bridges become important, higher than 30% [7]. Using the TRNSYS 17 simulation software, an original and accurate method has been developed by using techniques for the energy simulation in buildings that take into account the actual effects of thermal bridges, by replacing the zone of influence of the thermal bridge by its equivalent structure.

The compositions of the walls and the thermal insulation have thus the effect of a thermal barrier that slows down the losses during the cold period [8]. Its impact on the thermal inertia of a hollow-brick wall is more efficient in winter time than that on a stone wall [9]. The most advantageous solutions for energy savings are the use of stone and sandwiching expanded polystyrene as an insulator between two brick layers. Energy savings may reach up to 58% with a payback period of 3.11 years [10]. Experimental comparison was performed on three existing buildings with different wall compositions. Parametric dynamic analyses (Energy Plus, CFD Fluent) were performed in order to assess the impact of the different solutions to be recommended for their renovation. The results showed that using thick thermal insulation resulted in overheating problems when coupled with high thermal mass. The resulting discomfort can be resolved during summer by resorting to a strategy of mixed insulation, using a ventilated external insulation layer.

Summer days with high temperatures can only be compensated with nocturnal ventilation or some other passive cooling system [10]. An experiment was conducted on two cells with 20 cm-thick vertical walls and a 15 cm-thick roof with external thermal insulation. One cell was kept permanently closed, night and day, while the other was ventilated during the night by opening the window. Thanks to nocturnal ventilation, the interior temperature of this cell was 2 to 3°C below that of the control cell (non-ventilated) [11]. The obtained results show that integral thermal insulation of the envelope of the first building meets the conditions of indoor thermal comfort during the summer. For the second building, despite indoor nocturnal temperatures that were higher than the outside air, natural nocturnal ventilation could get rid of the overheating pockets trapped inside. Integral insulation is interesting in the summer; however, it slows down the free solar contributions during winter days.

The economic interest of super-insulators such as aerogels should improve through new technological breakthroughs. There would thus exist a very important need for renovation using thin thermal insulators, such as aerogels [12], which could demonstrably contribute to the preservation of indoor thermal comfort, particularly in the field of thermal rehabilitation of buildings, by reducing heat losses by around 46% and offering superior thermal characteristics, even reducing the impact of thermal bridges [13] when compared to a conventional thermal insulator, achieving conformity with thermal resistance regulations while saving 20 cm in thickness [14]. Dynamic parametric analyses using the Ecotect energy simulation software were performed in order to assess the impact of different insulating nanomaterials that could improve the thermal performance of a building during the summer. The efficiency advantage of insulating nanomaterials when compared to traditional insulators reside in the time lag achieved by the nano-insulators: 16.48hrs for walls and 12.66hrs for roofs. These ultra-efficient technologies are certainly worth considering when devising energy policies in the building and construction sector.

Research has confirmed that the thermal and energy performance of a building depends on the insulation of the building together with other parameters, among which are the kind, location and thickness of the insulator, the shape of the building, daylight exposure, the construction materials used and thermal inertia. Hence, the development of high-performance, low-thickness insulation systems tailored to the provisions of internal and external insulation seems to be a major consideration in the nation-wide problem of improving the energy efficiency of the existing buildings and soon of the “new” buildings.

2. INVESTIGATION

2.1 Description of the building under study

The study has been performed on an unoccupied building with a North-East orientation, at a 120° azimuth, and comprising four superimposed levels. The sample includes the ground, first, and last floors (Fig.1) containing respectively the home, the mess, and the store. The selection of these spaces aims at assessing the effect of the external insulation on the energy performance of the building.

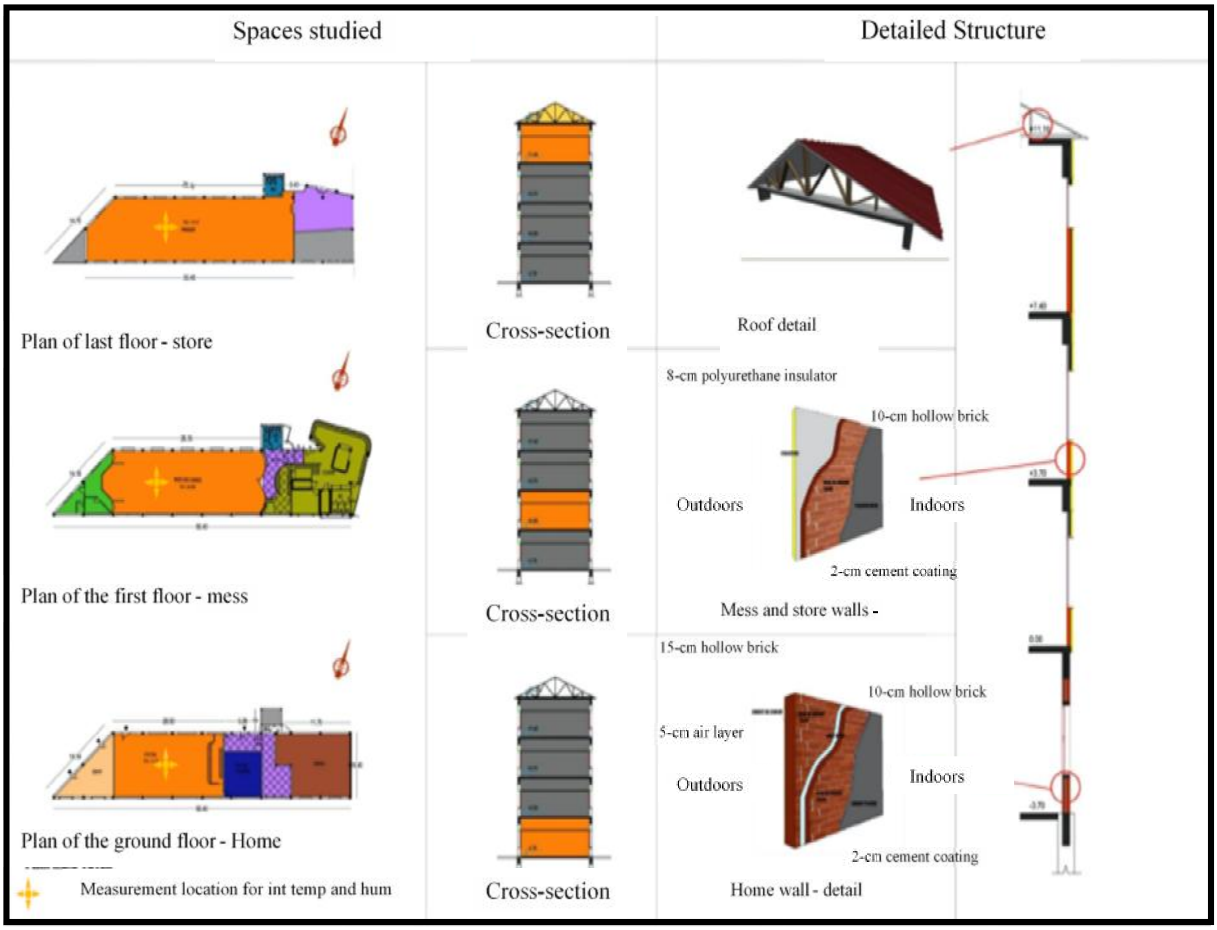

Fig.1. Plans and wall structure of the sample spaces studied

2.2 Infrared thermography of the building

Fig. 2b shows a thermal image, taken with thermal camera, of the north-eastern façade of the building under study. This diagnostic was performed during a February night. The image reveals the presence of thermal bridges. The heat losses occur at the various junctions between levels; however, the image also demonstrates the effectiveness of the thermal insulators fixed to the external walls of the mess-store block, while the ground floor (home), devoid of insulator, exhibits considerable temperature leaks.

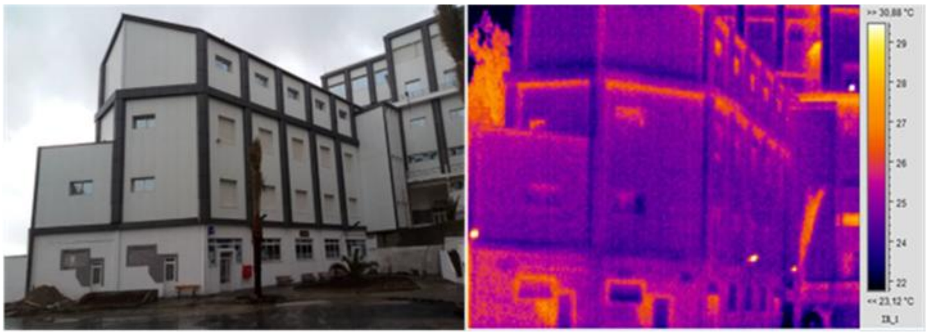

Fig. 2. a) External façade of building under study; b) Infrared thermography

3. RESULTS AND DISCUSSION

3.1 The effect of external insulation on thermal comfort

A measurement campaign was performed to record the air temperature inside and outside the spaces part of the sample. A series of measurements were recorded on the roof of the store and on the walls of the home in the ground floor, which, unlike those of the mess and the store, were not insulated.

3.1.1 Summer indoor temperature (scenario (01) no ventilation)

In the first scenario (No Natural Nocturnal Ventilation), the maximum air temperature measured was 28.93°C at 19:00 inside the mess, 29.90°C at 18:00 inside the home (ground floor), and 31.67°C at 17:00 in the store (floor under the attic). The difference in maximum (recorded) temperature is thus 0.97°C between the home and the mess, and 2.74°C between the mess and the store. The external temperature having reached 33.67°C at 14:00, the time lag for the mess and the home is between 4 and 5hrs, shown in Fig.3.

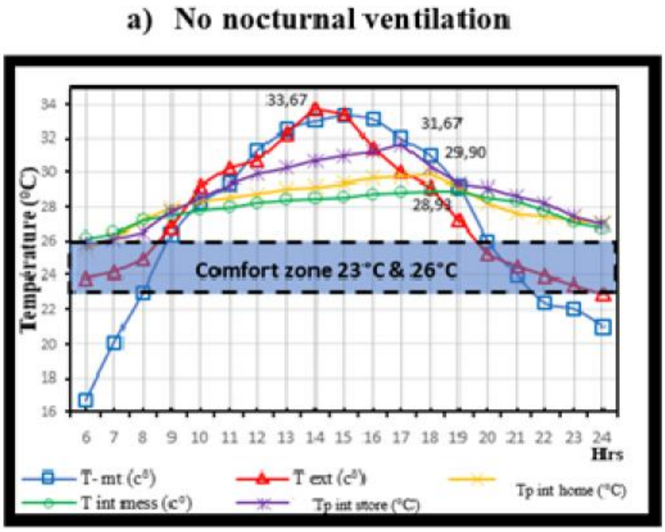
a) No nocturnal ventilation

Fig.3. Variation of average summer air temperature in the home, mess and store (18-19-20, August 2016)

3.1.2 Summer indoor temperature (scenario (02) with natural nocturnal ventilation)

In the second scenario (With Natural Nocturnal Ventilation), Fig.4 shows the maximum air temperature measured inside the mess, the home, and the store was, respectively, 27.20°C, 27.77°C, and 32.90°C, while the external air temperature and outdoors temperature were 33.70°C and 34.93°C. The curves for the mess and the home are almost flattened during the whole day, unlike that of the store which evolves gradually following the external air temperature curve. External insulation of the mess, using polyurethane, which has a very low thermal conductivity (λ=0.022 Wm-1K-1), has contributed to the lowering of heat intake, resulting in a temperature difference of 4.73 to 6.5°C with a time lag of 4 to 5hrs. Thus, external insulation combined with natural nocturnal ventilation is effective in reducing indoor overheating. This effect is felt in the lowering of the maximum air temperature by 1.73°C in the mess.

External air temperature at night in a semi-arid climate during the summer contrasts with daytime temperature; it varies between 18 and 22°C. Hence, the heat captured, trapped and stored during the day escapes gradually during the night from the inside to the outside until equilibrium is reached. On the one hand, natural nocturnal ventilation of the spaces studied contributes in removing indoor heat by cooling the internal surfaces of the walls, thus allowing quick achievement of equilibrium in temperature between the outside and the inside. On the other hand, the impact of external insulation on the wall temperature ensures an indoor air temperature that is virtually stable all along the day by also taking advantage of the inertia of the walls (day/night time lag) especially that there are few thermal bridges.

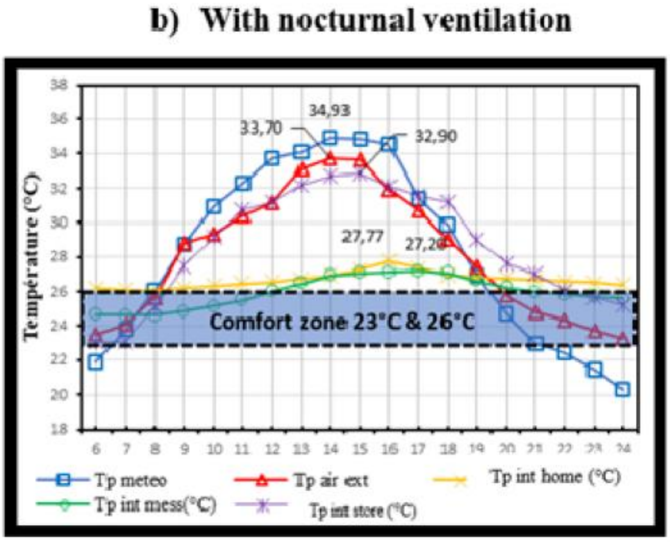
b) With nocturnal ventilation

Fig.4. Variation of average summer air temperature in the home, mess and store (21-22-23, August 2016).

3.1.3 Comparative study between scenario (01) and scenario (02)

Careful comparison between the average temperature readings of maximum indoor air temperature for both scenarios considered (with and without natural nocturnal ventilation) has allowed us to deduce that temperatures in the spaces studied (home-mess) are on average 1.93°C higher in the first scenario than those with natural nocturnal ventilation. This show that the heat stored during the day is not completely restored to the outside and remains trapped indoors due to the closed windows, the external insulation on the walls of the mess and the store and the air layer in the walls of the home.

During the summer, external thermal insulation coupled with natural nocturnal ventilation proved an effective alternative solution to improve the performance of thermal insulation. Sensible combination of these two parameters (insulation and natural nocturnal ventilation) allows the evacuation of the heat stored indoors as well as compensation between gains and losses and improvement of the sequential inertia of the wall, thus efficiently contributing to the slowing down of losses from the inside to the outside, particularly during the night when the external temperature is moderate, so that the indoor temperature remains relatively stable. This observation concurs with the opinion of several researchers working on the combination of external thermal insulation with natural nocturnal ventilation, such as [8-10-16] adopting a mixed insulation strategy and using a ventilated layer of external insulation.

3.1.4 Interpretation of the results of the winter period (home, mess, store)

An intense cold wave, including two consecutive days of snowfalls at altitudes of 400m and above, occurred during the period of the study. According to Fig. 5, the average temperature inside the home registered a small amplitude of only 3.23°C between a maximum of 17.92°C at 16:00 and a minimum of 14.69°C at midnight. In the mess, the amplitude was of 4.01°C between a maximum of 18.70°C at 16:00 and a minimum of 14.69°C at midnight. In the store, the amplitude was of 3.62°C between a maximum of 19.09°C and a minimum of 15.47°C. External temperature varied between a maximum of 7°C and a minimum of 2°C.

A significant difference of 12.77°C, 13.30°C, and 14.14°C is observed between the external temperature at 06:00 and the home, mess, and store, respectively. Thus, the temperature inside these spaces is gradually balanced and is higher than the temperature outdoors. Despite a 1°C drop in external temperature, the thermal insulation constantly opposes drastic decreases in temperature during winter, acting rather as an obstacle (barrier) against losses of indoor heat than as an absorber of external energy. Actually, the behaviour of the thermal insulation combined with the thermal inertia of the wall makes it a retarder that resists all temperature fluctuations [1] during winter, protecting the building from losses or leaks through convection and conduction.

Obviously, heat transfer originates in temperature differences and occurs every time a temperature gradient exists in the wall (Fig. 5). Transfer of heat flow by conduction through the wall is opposed by thermal resistances. These depend primarily on the conductivity and thickness of each component, which results in rather favourable time lag properties.

Consequently, external thermal insulation combined with the thermal inertia of the wall (hollow brick), through its capacity and thickness, highlights the optimal management of heats flows which is more efficient during the winter when the free solar radiation is more desirable, especially when there is a high ratio of transparent to opaque surfaces on the wall. This agrees with the results of a study by [2], demonstrating the effect of thermal insulation during both the cold and the hot seasons, justified by significant decreases in (indoor) air conditioning and heating periods.

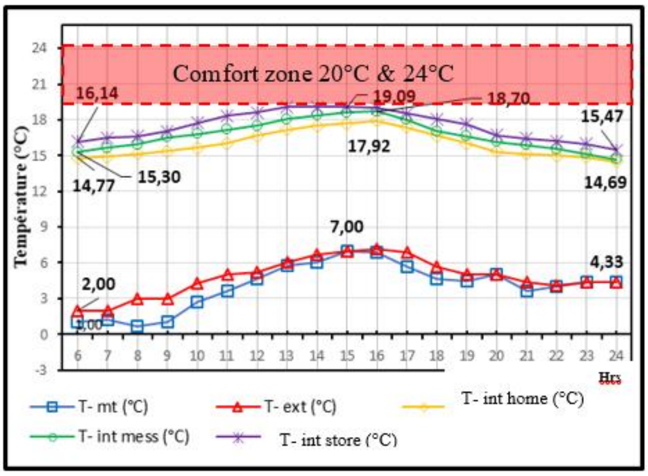

Fig.5. Variation of average winter air temperature in the home, mess and store (16-17-18, January 2016).

4. MODELLING

The study conducted on the three spaces in the sample allowed us to obtain experimental results and draw conclusions on the thermal behaviour of the examined samples. The impact of thermal insulation on air temperature inside the different walls was highlighted. In order to generalise these results to other scenarios, a numerical simulation was necessary to consider study cases that are impractical to implement in reality. To this end, we studied the thermal behaviour of these different spaces using the TRNSYS 17 software (fig. 6). The weather conditions are measured in situ and integrated into the software. A multizone model (type 56) is used.

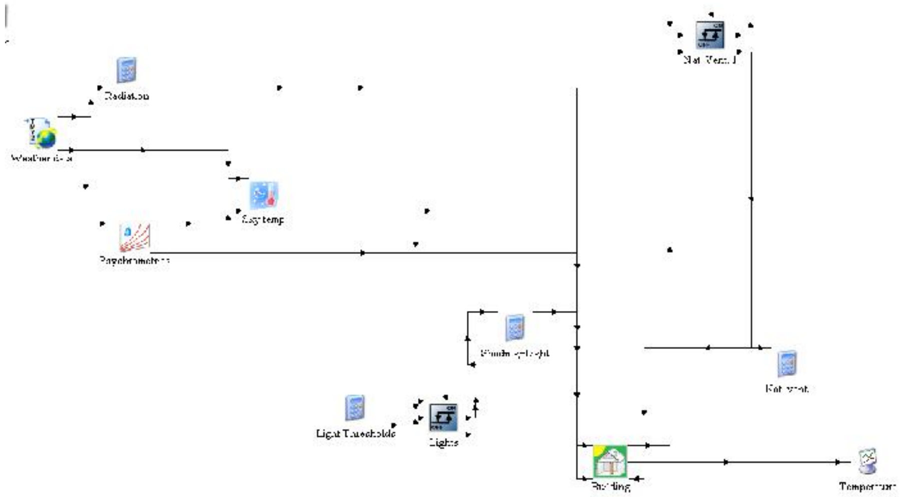

Fig.6. Modeling of the building under the TRNSYS environment

4.1 Effect of natural nocturnal ventilation on energy consumption

The successive results show that Natural Nocturnal Ventilation has a significant effect on decreasing the operative temperature during the summer. This decrease would in turn lower the energy consumption of the sample spaces. Fig.7 illustrates the variation of air conditioning consumption in the home and the mess during the summer (June-August) both with and without natural nocturnal ventilation. We can observe that natural nocturnal ventilation leads to a decrease in air conditioning consumption. These results are in agreement with [10]. For the home, there is a decrease in consumption from 10720 kWh to 9029 kWh, representing a 15.77% gain. For the mess, the decrease is of 15.15%, from 3986 kWh to 3382 kWh.

Fig.7. Variation of air conditioning consumption for the home and the mess during the summer

4.2 Effect of the composition of the wall on energy consumption

The effect of the composition of the external wall on the energy consumption of the building is illustrated in Fig. 8. The figure shows that energy consumption is at its lowest, a 2.32% decrease compared to the real-life case (mess), when using an ecological insulator, sheep wool (case 4). Using an extra air layer in the mess wall (case 3) also leads to a decrease, of 1.95%, in the energy requirements of the building. However, using a double-brick layer (case 1) or internal insulation for the whole building (case 2) increases energy consumption by 0.41 and 0.18% respectively. Using a super-insulating aerogel on the outside with a 2-cm thickness (case 5) results in a significant decrease in the energy consumption of the building, 18.46% less than in the real-life case shown in Fig.9.

The effect of the composition of the building walls is clear and leads to the decrease, or increase, in the energy consumption of the building. The best results were obtained by using an aerogel (super-insulator) with better thermal characteristics than those obtained in the real-life case (external polyurethane insulation). Effectively insulating a building (or part of it) leads to overheating during the summer and causes an increase in the energy consumption of the building, as confirmed by [8]. Adding an extra air layer to the external insulation of the mess (case 3) [16] is also a beneficial solution and is well suited for improving the effect of insulating the building envelope and preserving its dynamic behaviour.

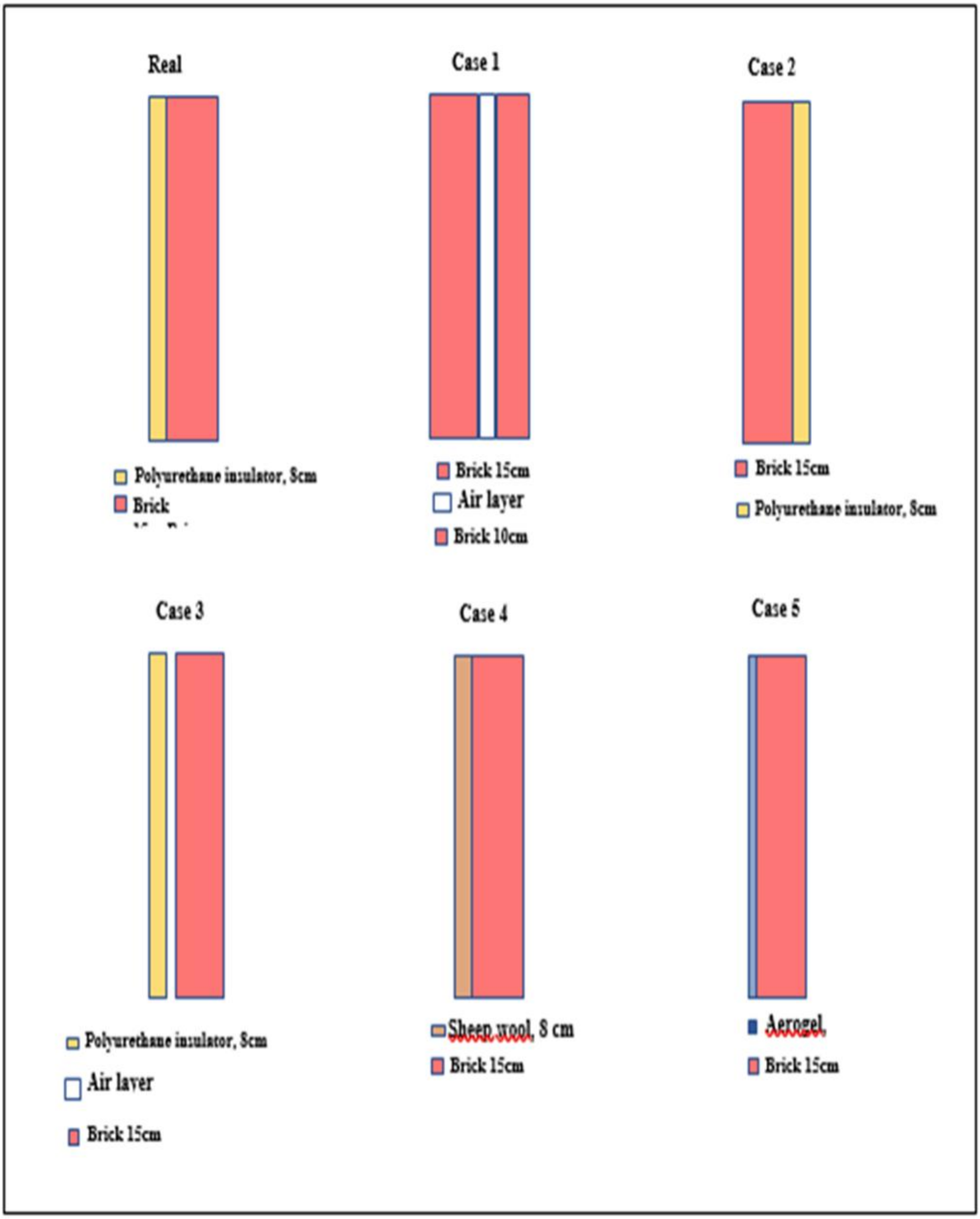

Fig.8. Schematic representation of the composition of the walls in the cases considered

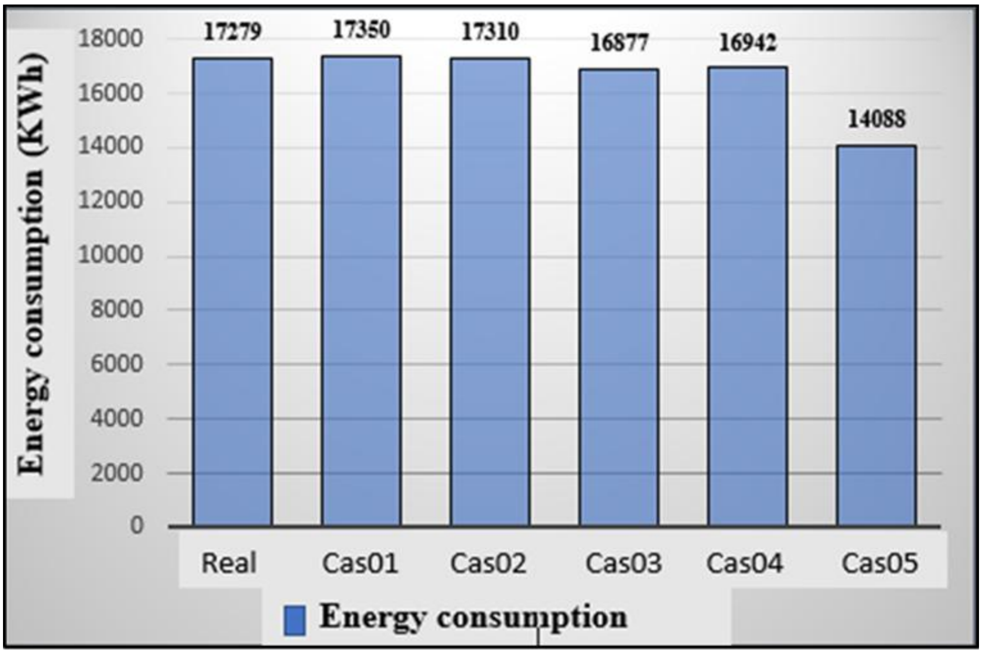

Fig.9. Variation of yearly energy consumption with the case studied

4.3 Effect of the type of insulation and nocturnal ventilation on energy consumption

Thermal insulation and nocturnal ventilation improve the energy performance of the sample spaces. The use of thermal insulation as a passive device allows the lowering of energy consumption for heating, albeit with a possible increase in air conditioning consumption. This increase is essentially due to the weak thermal conductivity of the insulator combined to the inertia of the wall which trap the heat indoors and slow heat transfer to the outside. Combining the two solutions (improved thermal insulation and natural nocturnal ventilation) allows a significant decrease in energy consumption. According to Fig. 10, Case 5 (thermal insulation coupled with natural nocturnal ventilation) exhibits a considerable decrease in energy consumption, 18.76% less than in the real-life case, in agreement with [17], while Case 4 (wall with ecological insulator) the gain is only 2.32%.

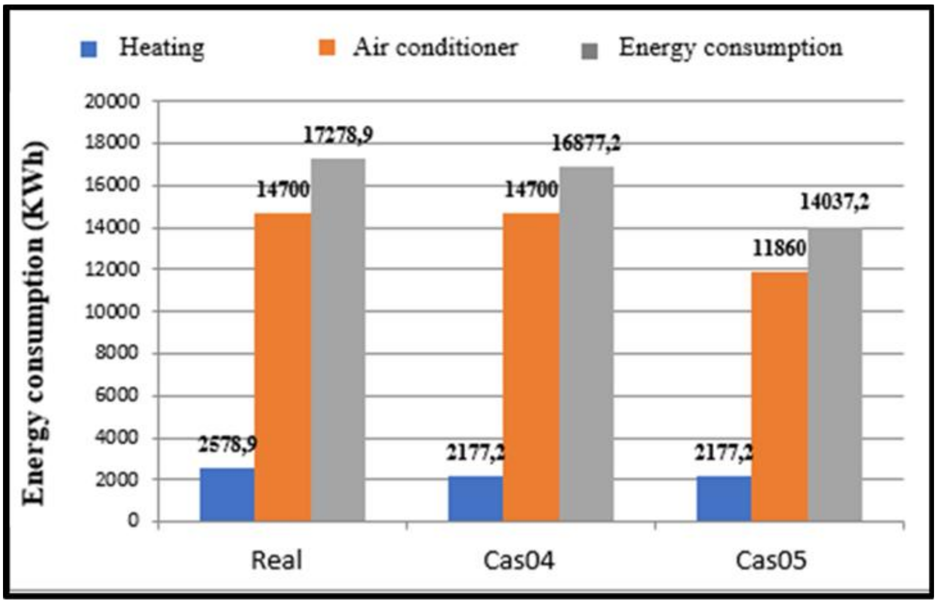

Fig.10. Variation of the yearly energy consumption with the case considered

5. CONCLUSION

Effectively insulating a (part of a) building in summer leads to overheating that may result in an increase the energy consumption of the building. The combination of thermal insulation and natural nocturnal ventilation allows the improvement of the thermal performance of the spaces studies. The following conclusions are drawn from this study:

- Using thermal insulation on the outside as a passive device allows the lowering of energy consumption for heating; however, it may also lead to an increase in energy consumption for air conditioning.
- The most appropriate solution to remove the temperatures trapped indoors is natural nocturnal ventilation, which allows cooling during the night; since the structure of the external walls preserves this coolness during the day, the air temperature indoors will be closer to the thermal comfort zone.The combination of the two solutions (thermal insulation and natural nocturnal ventilation) allows a significant decrease in energy consumption.
- The effect of the composition of the building walls is clearly felt; it results in a decrease or an increase in the energy consumption of the building. Adding an air layer to the external insulation of the mess improves the thermal comfort inside it and

decreases energy consumption; it is a beneficial solution that is very practical. The best results obtained in this study came from the use of an aerogel (super-insulator) with thermal characteristics better than those in the real-life case (mess).

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