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Assessment of the impact of aerogel materials on the energy consumption of hotels under the coastal Mediterranean climate

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ABSTRACT/RESUME

Abstract: *With the increasing emphasis on sustainable development and climate change issues, there is an urgent need to address the issue of greenhouse gas emissions induced by the misuse of energy appliances in buildings. In Algeria, the building sector is the most energy-intensive, with the tertiary sector representing a very important fraction given its enormous energy consumption. As hotel construction is a current project in the country, they are addressed in this research which aims to highlight their needs for heating, cooling, lighting. More precisely, an investigation combining experimental work (air and surface temperature measurements and thermography) and numerical simulation (using TRNsys V17) was conducted on a prototype (an urban hotel) in Algiers, a city with a coastal Mediterranean climate. A diagnosis of the actual thermal comfort conditions and the results revealed that the envelope is not protective from external climatic agents mainly due to heat loss through walls, roofs, and floors, windows. To overcome this challenge, a proposal to integrate new insulation materials based on aerogels (silica aerogels) allowed a significant reduction in energy loads. This allowed reaching comfort levels in the study rooms (more than 53% reduction for heating needs and 43% for cooling needs compared to non-insulated rooms).*

I. Introduction

Combating climate change is one of the challenges of this century. The majority of studies show that anthropogenic greenhouse gas activities are the primary contributor to global warming by increasing ambient air temperature and energy consumption in the environment [1]. According to the International Energy Agency (IEA), global energy consumption will increase by 2.3% in 2018, and is considered to have had the sharpest growth in the last decade [2]. One of the most common concerns of building designers nowadays is to seek a balanced reconciliation of local climatic parameters and available renewable energies to accomplish a healthy and sustainable architecture.

In Algeria, the building sector is the first in terms of energy consumption (with a rate of 43% of the overall national amount) and the third in terms of GHG emitter (with 16% of the total amount of GHG emitted on the country) [3]. Given the increased development of the tourism sector, it has become one of the most important sectors for economic development in most countries [4]. Hotel construction is considered to be one of the largest emitters of greenhouse gases; in 2005 it emitted 274 million tons of CO_2 worldwide, 21% of the total quantity emitted by the world tourism sector [5], The hotel establishments in the study are known worldwide as large energy consumers in the tourism sector. For example, in 2011, they ranked among the top five with an estimated energy consumption of 97.5T wh [6] and an average energy intensity ranging from 69 to 689 KWh/year [7]. These values were recorded mainly at the room level, where the comfort requirements of the guests involve continuous use of heating or cooling. The cost of energy consumption, very recently estimated at nearly half of total energy consumption, was not considered [8].

In the last decade, the lack of accommodation in institutions has been addressed. Unfortunately, the latter are often built with little attention to regulatory and environmental requirements. A kind of construction standard has become widespread throughout the country, despite the differences in climatic characteristics that the most energy-intensive buildings unfortunately often suffer. The climatic policies aim to improve the energy efficiency of new buildings; however, existing buildings have been neglected due to the difficulties of refocusing when improving energy performance. Therefore, it becomes urgent to find sustainable solutions for this type of building [9].

Regarding Algeria, a large number of hotels have been built recently among which a high percentage (50 %) are located in the coastal areas [10]. These latest are characterized by the Mediterranean climate known for its hot and dry summers ranging between 25 °C and 40 °C and its mild and humid winters averaging 5 °C, and its rainy intermediate seasons [11]. In this context a study of the impact of building envelopes on environmental and energy for three touristic establishments (hotels) using a life cycle analysis approach was developed [12]. The results revealed the option to reduce the energy requirements of both traditional and standard hotel envelopes by assigning low-consumption building scenarios. In the same scope, Kaoula undertook a research work which aim was to reduce the pressure on the environment by intervening on a heritage hotel building located in central Algiers through a comparative LCA with a low consumption hotel in France [13]. The findings showed that in order to reduce environmental impacts generation for a new building under the Mediterranean climate, it would be necessary to introduce low- energy eco-techniques solutions. These would offer an environmental balance with a good thermal inertia of the materials, a generic insulation of the vertical and horizontal walls, the reduction of thermal bridges by external insulation and the low-emission double or triple glazing. The consideration of these solutions allows for better environmental preservation and conservation of energy [14].

Literature review of aerogel materials in building:

The exterior façade being the subject of this article, the current study aims to provide evidence of the effects of its important active architectural element upon energy loads, with a particular interest to its materials characteristics. The considerable progress made recently in the generation of new materials called "super-insulation materials," characterized by their energy performance two to three times higher than traditional insulators [15], has encouraged the deepening of this topic. One example is aerogel-based materials with thermal conductivity (λ) of up to 0.015 $W \cdot m^{-1} \cdot K^{-1}$ [16] which allow a significant improvement in the building insulation process (by neutralizing the three heat transfer modes) [17].

The qualities of aerogels impact not only temperature but also the sound environment as they offer a remarkable ability to reduce surrounding noise [18]. Therefore, they are innovative thermal and acoustic insulation materials with extremely light solid foams (with a network of nanometric porosities composed of up to 99.8% air) [19] and can be subdivided into five types: silica, metal oxide, organic, carbon and hybrid aerogels. The development of silica aerogel technology is observable nowadays, and despite their excessively high price, they are restrictively applied to buildings. Yet, researchers believe that they could quickly become the most attractive materials in the future due to the development of cheaper innovative manufacturing techniques [20].

Indeed, with respect to the inherent advancement of aerogel materials, two research groups with clearly different but complementary objectives have been observed.

1-The combination of aerogels and standard materials:

The first group is dedicated to the development of new materials by combining aerogels and standard materials. For example, aerogels and bricks (called Aero-bricks) have been produced, reducing the thermal conductivity (λ) from 0.091 to 0.059 W m-1.K-1 with a corresponding U-value of only 0.157 W/ (m2 K) [21]. Based on these results, Ganobjak and Josephine [22] confirmed the performance of this combination for insulation and high-performance design of building envelopes after considering the optimization of the Aero-brick topology.

On the other hand, Liu [23] developed a SiO_2 aerogel material (FC-SA) reinforced with concrete foam whose thermal conductivity of the FC-SA composite was as low as 0.049 W/m K along with a 48.4% decrease compared to aerated concrete. They also provided clear evidence of reduced energy consumption by using FC-SA instead of traditional concrete materials. Considering all European climates, Aspen Aerogels Company, U.S.A. has developed a high-performance thermal insulation material called SPACELOFT for residential and commercial building enclosures. This material is very versatile, saves floor space, and improves energy efficiency [24].

2- The evaluation of the performance of aerogels materials:

The work of the second group of researchers was mainly limited to experimental and simulation studies to test and confirm the effectiveness of aerogel materials in reducing the energy consumption of interiors. Lang [25] revealed through simulation work that compared to more usual insulation materials, silica aerogel improves the energy efficiency of buildings by reducing the annual heating cost at a rate of 50%. (Ibrahim Mohamad [26] showed that the addition of aerogel coating on the exterior surface of uninsulated or already internally insulated walls significantly reduces or eliminates the risk of moisture, also reduces heat loss on the walls. Buratti [27] stated that applying these innovative materials can be a useful tool for the insulation of new buildings and the renovation of existing buildings. The best value of thermal conductivity obtained from manufacturers is about 0.015 W/m K.

Following this state of the art, the same authors [28] showed through energy simulations for a case study under different climatic conditions (hot, moderate, and cold) the reduction in energy demand for heating and cooling of silica aerogel glazing systems compared to conventional systems. (Huang [29] proposed a super-insulating glazing system filled with silica aerogel in a commercial building in Hong Kong, proving that the energy consumption of the HVAC system was reduced by 4 to 7%. Saio [30] analyzed through a series of numerical simulations using silica aerogel to renovate a historical building to achieve a high level of energy improvement. The study shows a reduction in heating demand of about 40% with aerogel and 25% with traditional insulation.

Yang [31] showed through numerical and experimental study that aerogel insulation panels (AIP) have 20% and 40% decreases in the internal temperature fluctuation range and heat flow, respectively, compared to traditional insulating walls. Belili [32] reported that the use of a super-insulating 2-cm-aerogel allow energy savings of 18.46% of the building study. Oualid [33] showed through numerical simulations that the use of aerogel insulation in building allows a reduction 50.90% in annaba city and 52.25% for the city of Setif and 38.72% For the city of Biskra.

From this premise, the field investigation of the proposed study focuses on the effective contribution of silica aerogel material applied to the studied enclosures (hotel rooms), where a diagnosis of the effective thermal comfort conditions was established through air and surface temperature measurements and thermography in winter and summer. After data collection and analysis, a numerical simulation was carried out using TRNSYS software to compare cooling and heating needs under existing conditions and after applying innovative aerogel-based insulating materials (silica aerogels) combined with solar protection in summer.

II. Materials and methods

II.1.Climatic conditions

Algiers is known for its coastal temperate Mediterranean climate with long, hot, humid summers and mild, rainy winters [34] . According to the psychometric diagram of the concerned city (Figure 1), it is clearly shown that without passive strategies, the comfort conditions would be ensured for only 10.6% of the hours throughout the year. Beyond this rate, some strategies are required to achieve the desired thermal comfort level**.**

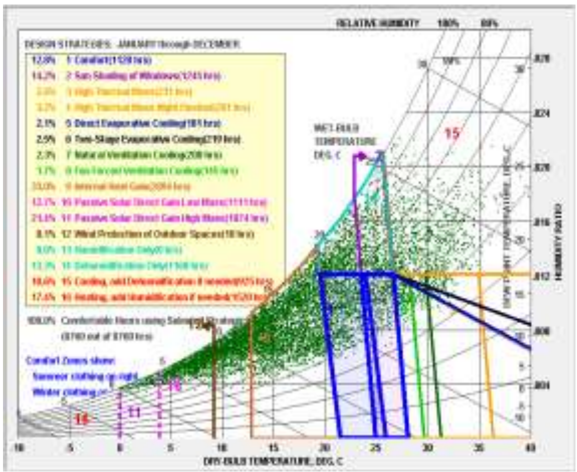

Figure 1. *The psychometric diagram of the city of Algiers. Source : Climate consultation software 6.0 : https://climate-consultant.informer.com/*

The analysis of the climatic data in Figure 1 allows identifying the most relevant strategies to meet the climatic requirements of Algiers. Specifically, enhanced thermal insulation and passive heat gain would provide 33% hours of comfort without supplementary heating in winter. While to achieve summer comfort, a key strategy would be to provide windows with solar shading for at least 14.2% of the hours, which would help the indoor ambient temperature stay within the thermal comfort zone.

II.2. Case study

This study investigates a 9-story urban hotel in Algiers (north-central Algeria), its main facade is exposed to northwest orientation, the secondary one is exposed to the South-East (Figure 2.a). Ibis hotel is rectangular and includes 264 rooms and other facilities (restaurants, coffee-bar, offices). Moreover, it represents a series of similar buildings owned by an international hotel chain that has established ten hotels in the country since 2010. The first room taken as a case study is located in fifth level floor in the South-East orientation, it has a rectangular shape, its treated floor area is 13.4 m² its characteristic length is 5.60 m and the width 3.1 m and its depth is 3.2 m as illustrated in (Figure 2.c). where the surfaces selected for measurements are the southeast window and North-East adjoining wall. The seconde room taken as a case study is located in fifth level floor in the northwest orientation, it has a rectangular shape, its treated floor area is 12.8 m² its characteristic length is 5.60 m and the width 3 m and its depth is 3.2 m. as illustrated in (Figure 2.c). where the surfaces selected for measurements are the northwest window. Details of this investigated rooms are shown in Figure 2.

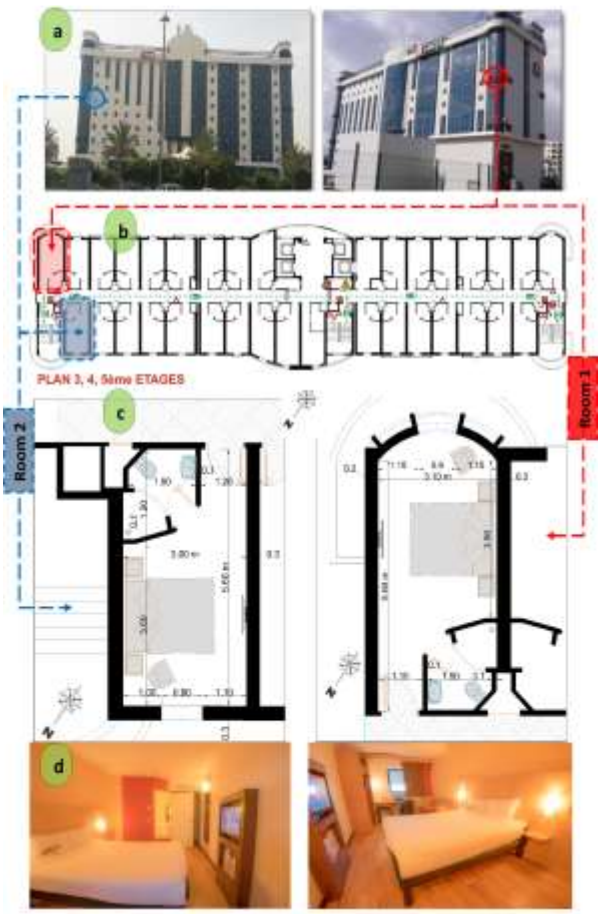

***Figure 2. a**. facades views of ibis hotel **b.** Floor plan view of hotel **c.** plan of investigated hotel rooms **d.** interior views of the rooms.*

II.3. The investigation reports

II.3.1 In situ measurements and energy simulation

To identify the main thermal problems inside the studied hotel rooms, in situ measurements were carried out. The data were collected by measuring instruments (Figure 3): an infrared thermometer (a) to measure surface temperatures inside and outside the walls and glazing, a temperature and humidity Data Logger to facilitate the work between rooms (b), a thermo-hygrometer to measure air temperature and relative humidity (c). All the measured values were used to validate the numerical model made with the software (TRNsys V17).

***a.** Infrared thermometer* ***b.** Thermo-hygrometer*

***c.** Temperature and humidity data Logger* ***d.** Thermal Imaging Camera*

***Figure 3.** Measuring instruments.*

Simulation software

The TRNSYS process is a dynamic simulation environment that allows for a good simulation of the behavior of a complex system, such as a building; it has been available since 1975. Based on architectural data and the thermo-physical properties of the material, an analysis of the thermal behavior of the samples was carried out using the “TRNSYS V 17” software.

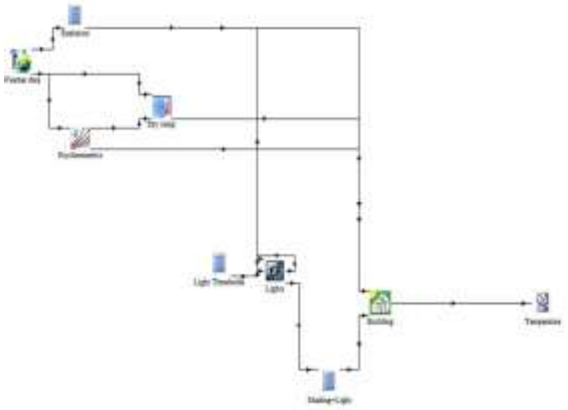

Figure 4. *Local modeling under the V17.TRNsys environment.*

II.3.2.Thermography of facades

The camera works by presenting a color scale showing relative differences in temperature, with red or white as the warmest and blue or purple as the coolest. In this study, we used a thermal image camera called Trotec EC040 (Figure 3.d). The inspection was mad on the month of February 2020 in the afternoon, outside temperature being 6 °C.

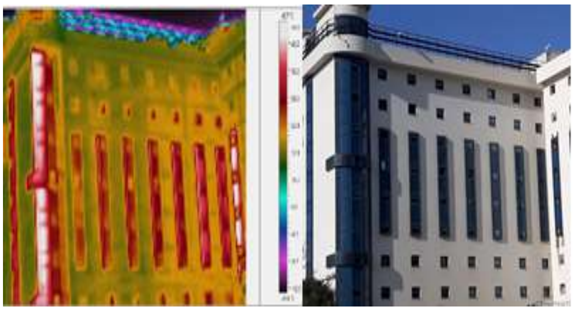

Figure 5. *On-site infrared thermography of exterior facade.*

The figure 5 shows a thermal image of the South-East where the average temperature on the wall is 11 °C, the windows and structural elements has not been properly insulated and there is a heat loss that can become significant over time, the temperature indicates 20 °C to 40 °C on comparing with the wall of 11 °C,it is clearly indicating the inadequacy or lack of insulation by the large areas colored in red which indicate an apparent surface temperature much higher than the rest of the hotel envelope.
In Figure 6 the thermal images in the interior rooms, the color contrast clearly shows the intense presence of thermal bridges, it’s showed that many sections are not insulated, as indicated by the warmer colors.

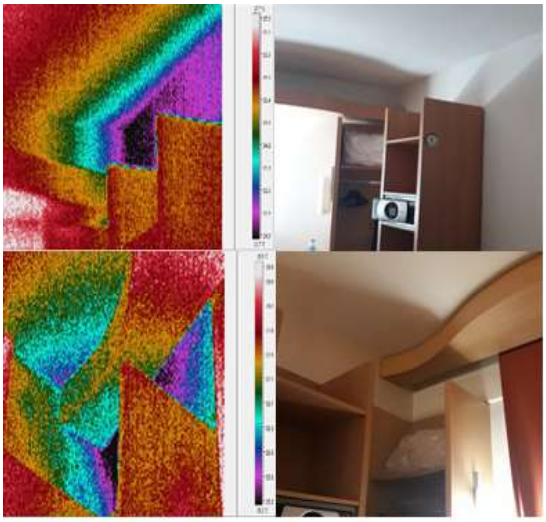

Figure 6*. Infrared thermography of interior Rooms.*

III. Results and discussion

III. 1. Validation of air temperature measurement results

Comparing the measured and simulated room temperature variation in the two chambers in summer and winter shows a slight difference of 0.1 to 1.1°C, proving the simulation model’s reliability. For the summer period (Figure 7) in room 1 the outdoor and indoor temperature curves are almost equal at night. The inside temperatures are lower during the day (from 6 am to 8 pm). The outdoor temperature reached its maximum value of 34°C at 2 pm, while the indoor temperature reached this value of 31°C at 4 pm, i.e., a thermal shift of 2 hours.
It can also be noticed an amplitude of the interior temperature of 5°c between a maximum value of 31°c and a minimum value of 25°c. This is explained by the average thermal inertia of the brick. Moreover, for room 2, the temperature curves are parallel, i.e., the indoor temperature is lower than the outdoor temperature, which reaches its maximum from 34 to 3 pm, on the other hand, the indoor temperature of room 1 reaches its maximum from 29 to 4 pm. Thus, for Room 1, there is a thermal phase shift of 2 h due to the low thermal inertia of the brick that composes the envelope of the hotel. For the winter period (Figure 8), the amplitude between indoor and outdoor temperatures remains average with smaller fluctuations.

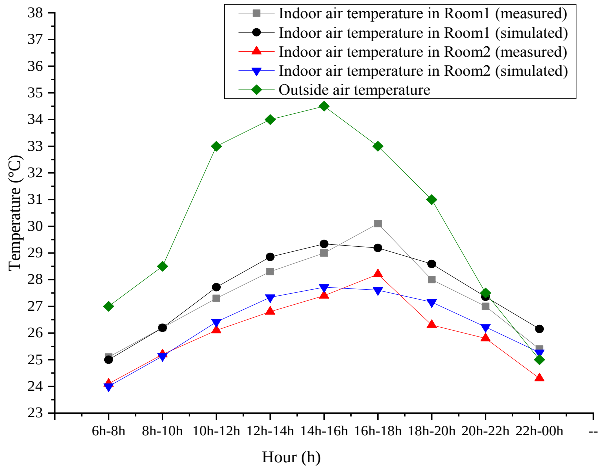

Figure 7. *Measured and simulated summer temperature in Rooms.*

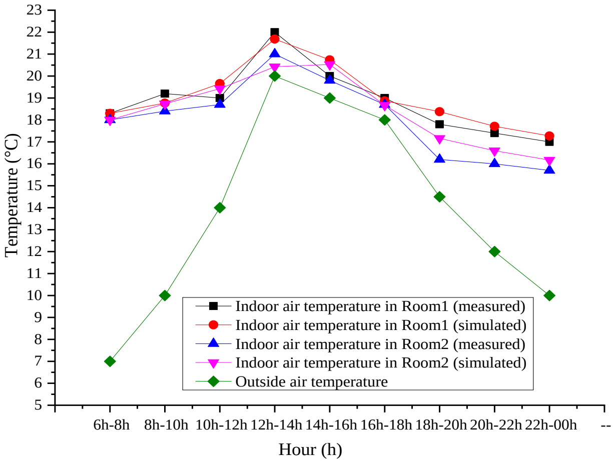

Figure 8. *Measured and simulated winter temperature in Rooms.*

III.2.Validation of surface glass window measurement results

A comparison of the measured and simulated surface temperature variations of the windows of the two chambers during the summer period shows a slight difference of 0.1 to 1°C (Figure 9).

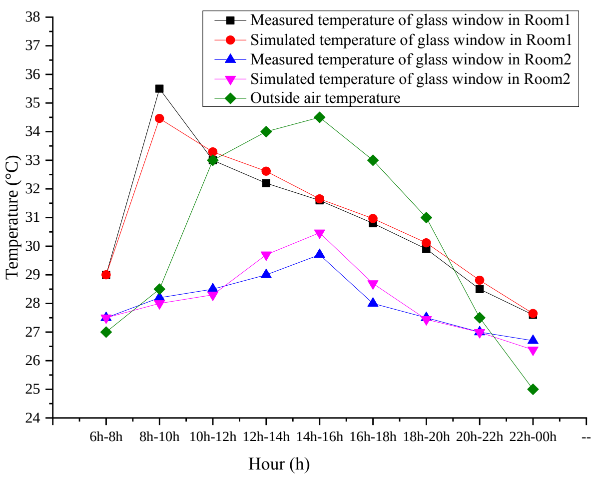

Figure 9. *Measured and simulated temperature results for glass windows in summer.*

III.3.Validation of the results of the surface wall measurements

Comparison of the measured and simulated surface temperature variation of the northeast facing wall during the summer period shows a slight difference of 0.1 to 0.9°C. According to Figure 10, the outside temperature decreases after the afternoon while the inside wall surface temperature increases to reach its maximum of 1.42°C at 8:00 pm. This is due to the effect of the inertia of the wall, which stores heat and releases it towards the inside with a thermal phase shift of 4h and an amplitude of 3°C.

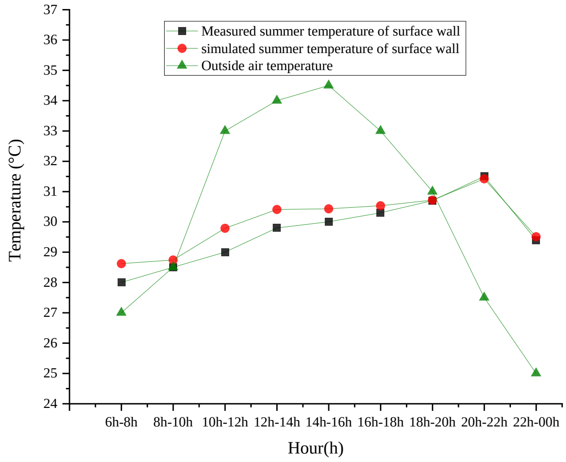

Figure 10. *Measured and simulated summer surface wall (northeast) temperature results.*

III.4. Evaluation of the impact of silica aerogel insulation materials on room energy consumption

The thermal images analysis and the experimental measurements' results indicate heat loss through the walls and windows. Therefore, based on the psychometric diagram of the study area, the proposed improvement consists of insulating the walls with a new material based on silica aerogel and integrating solar protection on the windows.

Table 1. *Composition of the exterior walls in the current state*

Reference	Thermal conductivity W/(m.K)	Thickness (cm)
Interior plaster coating	0.52	1
Airbrick	0.45	10
Air gap	0.29	5
airbrick	0.45	15
Exterior plaster coating	0.52	1

Table 2. *Composition of exterior walls after silica aerogels insulation integration*

Reference	Thermal conductivity W/ (m.K)	Thickness (cm)
Interior plaster coating	0.52	1
Airbrick	0.45	10
Silica Aerogels	0.02	5
Airbrick	0.45	15
Exterior plaster coating	0.52	1

III. 4. 1. Evaluation of energy consumption

In the current state the Room 02 is the most energy efficient in terms of heating and cooling energy demand. there is a difference between the two rooms of 82.9 kWh for heating needs and 13.8 kWh for cooling needs so there is an important decrease in the energy needs when orientation is changed (Figure 11).

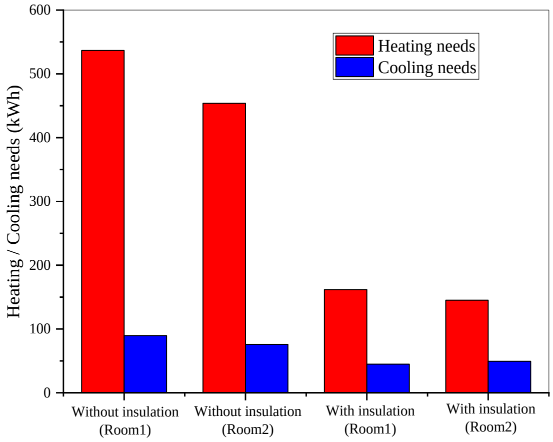

Figure 11. *Heating and cooling requirements for the cases studied.*

For Room 1, a reduction in heating requirements from 453.8 kWh in the current state to 145.2 kWh, a reduction of 68% after the integration of the silica aerogel insulation, for summer period a reduction in cooling requirements from 75.9 kWh in the current state to 74.3 kWh after the integration of the silica aerogel insulation a reduction of 2% of needs. since the windows are in double glazed, the application of solar protection is the most suitable which leads to a considerable reduction in needs, estimated at 49.3 kWh a reduction of 35%.

For Room 2, a reduction in heating requirements from 536.7 kWh in the current state to 161.01 kWh, a reduction of 70% after the integration of silica aerogel insulation, for summer period a reduction in cooling requirements from 89.7 kWh in the current state to 85.22 kWh after the integration of silica aerogel insulation a reduction of 5% of needs, for this, the integration of solar protection of the windows reduces the needs to 44.85 kWh a reduction of 50%.

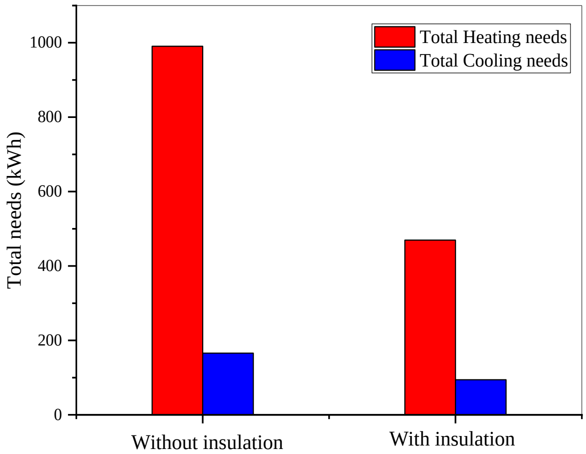

Figure 12. *total needs for the cases studied.*

For the total needs of the two rooms (Figure 12), a reduction in heating needs from 990.6 kWh in the current state to 469.61 kWh, a reduction of 53% after the integration of silica aerogel insulation, for summer period a reduction in cooling needs from 165.6 kWh in the current state to 94.15 kWh after the integration of silica aerogel insulation and solar shading of windows, a reduction of 43%.

IV. Conclusion

Accommodation buildings, especially hotels, represent a real threat to the environment because of their high energy consumption. In Algeria, a large number of hotels have been built in recent years, a high percentage of which are located in the Mediterranean area, where the region is particularly exposed to high humidity in summer and winter. The hotels envelope constitutes a key element in reducing energy. This paper aimed to evaluate the impact of silica aerogel insulation materials impact on affordable energy efficiency within hotel buildings in a humid climate (case of north-central Algeria). Thermography is a technique that allows to visualize and represent the temperature distribution on the part of the surface of a building. It is the distribution of this temperature that allows the detection of thermal irregularities. The analysis of the thermal images shows that there are heat losses at the level of the walls and the windows, which increases the energy consumption. Then series of measurements were carried out to validate the model developed under the TRNsys V17 environment. On this basis, we conclude that:

-The exclusive properties of aerogels offer different applications in building sector. The use of insulating materials based on silica aerogel leads to a considerable influence on the energy needs of the rooms studied.

-the integration of silica aerogel for the insulation of the external walls with a thickness of 5cm significantly reduces the heating needs (winter period) of the hotel rooms (53% compared to a non-insulated room).

-For the summer period, solar protection constitutes a good alternative of design with the integration of silica aerogel for the insulation of the external walls to reduce the air conditioning needs significantly; it reduces the needs to 43% of the rooms studied.

-The use of silica aerogel for building insulation can create an architectural challenge in Algeria, due to its great ability to reduce heating and air conditioning consumption. The results obtained show that obtaining high energy performance in Mediterranean climates is possible. This article is part of a larger study effort that aims to provide designers with a database to reduce energy consumption in hotels by integrating aerogel materials into the envelope.

Abbreviation and units

GHG: Greenhouse Gas Emission.

λ: the thermal conductivity in W/mK.

U: The thermal transmittance of a material in W/(m2·K).

FC-SA: the Foam concrete reinforced silica aerogel.

SiO2: Silicon Dioxide.

AIP: Aerogel insulating panels.

HVAC: heating, ventilation, and air conditioning.

APRUE: Agence Nationale pour la Promotion et la Rationalisation de l'Utilisation de l'Energie (original term in French; National Agency for the Promotion and Rationalization of Energy Use).

IEA: International Energy Agency.

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