Investigating Nanomaterials Performance for Energy Efficient Building Envelope

Fatma Ahmed Elbony
Department of Architecture/ El-Gazeera High Institute for Engineering, Fatma_bony@yahoo.com

Abstract:
Nano-based materials for energy efficient buildings have been receiving an ever increasing attention due to their advantages regarding to energy efficiency and environmental impact. For this purpose, this paper investigated the potential of using Nano-based materials represented in aerogel as a nano-based thermal insulation material and Nanogel glazing system to improve the efficiency of the building envelope and reduce cooling energy and achieve energy conservation in buildings through a simulation process conducted on an office building in smart village as a case study. Firstly the paper investigated separately the energy performance of these nano- based building envelope materials, it is found that there is a reduction in the total building energy consumption 2.17% and 4.93% respectively. The reduction in the cooling energy consumption was 3.15% and 7.41 %. Secondly the paper investigated using a combination of the two nano-based building envelope materials which resulted in 7.42% reduction in the total building energy consumption and 10.78% reduction in the cooling energy consumption.

Keywords:
Nanomaterials, Building Applications, Building envelope, Energy performance, Energy Simulation Tool

Paper received 15th February 2020, Accepted 25th March 2021, Published 1st of May 2021

1. Introduction

Regarding to the urgent need to reduce building energy consumption, building envelope design should be a key part of any long-term energy reduction strategy. The building envelope plays a strategic role in the energy and environmental performance of the building, significantly affecting the levels of indoor comfort [(3)]. The quality and energy efficiency of building envelopes are the most important factors that affect the energy consumed by heating and cooling equipment. Advanced building envelope design can reduce energy needs for cooling by minimizing heat gains in summer using some design elements such as, thermal inertia and highly reflective surfaces in roofs and walls to reduce summer overheating in hot climates; high-performance windows with low thermal transmittance and appropriate solar heat gain coefficient (SHGC); thermal insulation, shading, reflective surfaces and natural ventilation. It is a critical component consists of transparent and opaque elements, potentially able to regulate the flows of heat, solar radiation, and air. [(3)]

The selection of materials with appropriate thermal and optical properties for the building envelope shows a great influence over all aspects of the total energy balance. Transparent elements have an important in buildings in terms of energy demand, thermal comfort, and day lighting: most of the total energy losses (up to60 %) can depend on the windows, especially in highly glazed buildings, because the transparent systems have thermal performance lower than the opaque walls and are influenced by radiation [(4)].

Since the transmission heat gains are the largest through the building envelope, especially through the walls, finding the best solutions for thermal insulation of walls is a top priority when it comes to energy-efficient buildings. Thermal insulation is achieved by using building materials of low thermal conductivity, i.e. high thermal resistance, and by avoiding thermal bridges. Recent progress in the development of high performance thermal insulators is due to progress in nanotechnology and material science.

Nanotechnology revolution and the significance progress in material science are bringing dramatic improvements in building performance, energy efficiency. It produces many advanced materials and nanotechnology products with physical and mechanical properties greatly exceeding those of conventional materials. These new products may be used for thermal insulation of the building, giving superior performance with extremely reduced thickness, for glazed components allowing dynamic performance (smart windows), for surface treatment of building materials to improve their characteristics or introduce new ones

Nanotechnology may yield important improvements in the energy efficiency of the

This work is licensed under a Creative Commons Attribution 4.0 International License

building envelope. These in particular consist in [3] advanced insulating materials (Fiber Reinforced Aerogel Blankets, Vacuum Insulated Panels) with extremely reduced thickness; Transparent Insulating Materials (Aerogel TIMs) to combine day lighting with energy efficiency.

Problem

Building envelopes contributes approximately 50–60% of the total heat gain in buildings [1].

Solar gains comprise the main contribution of the envelope loads; it reaches 40%-50 [2]. The second contributor in envelope loads transfer is walls whose contribution differs between orientations.

Objective

The main objective of this paper is to discuss the effectiveness of implementing the recent innovations and technologies in thermal insulation (Reinforced aerogel blankets) and glazing systems (Nanogel windows) for building envelope to increase energy efficiency and energy savings. The final goal is to provide, using the nano-based-materials, an "efficient building envelope," capable of offering better performance compared to a traditional building shell.

Research methodology

Empirical study and modeling are frequently used in investigating the effect of using Nanomaterials on building energy consumption. Given the aim of this study, modeling was more appropriate as it allowed the flexibility to examine various types of building materials with different properties. Also, choosing modeling facilitated the connection to the previous research work done by the authors [5] upon which this study was based.

Significance

Several studies evaluated the impact of using thermal insulation materials and advanced glazing systems on the building energy performance, the significance of this study represents in investigating these nano-based materials through an existing building as a case study to conclude the efficiency of using these materials.

Nanomaterials' Building Applications

Nanotechnology can be used to create new advanced high performance building materials able to provide exceptional heat flow resistance performance. The main Nano-based building material's applications which affect building energy consumption may be divided into two groups, i.e., insulators by means of aerogel blankets, and in translucent form for high performance glazing. Aerogel blankets (composite of a silica aerogel and fibrous reinforcement), can be used in the entire building industry similar to the use of traditional thermal insulators. However, their current high economic cost means that they are only used where limited space. [2].

Nano-Based Insulation Materials

Building envelope insulation as a strategy to reach energy efficiency is normally achieved through the use of materials, which called Insulation Materials, with specific thermal and physics properties to give the various components to which they are applied high levels of thermal resistance, or R-value (m2/KW), thus reducing heat flows for the same environmental conditions. There is a number of different thermal insulation materials used in the building industry today. Conventional materials, such as glass wool, rock wool, expanded polystyrene (EPS) and extruded polystyrene (XPS), require a thick building envelope to reach a sufficiently low thermal transmittance.

Due to the progress in nanotechnology and material sciences, there are many advances in the development of insulating materials. It has allowed production of high performance thermal insulators with a thermal conductivity below 0.02 W/mK, compared to an average value of conventional insulating materials in the range of 0.025-0.040 W/mK [3].

Depending on the literature review, **Nano-aerogel thermal insulation** has been presented as a high performance thermal insulation material with unique structure resulted in exceptional material properties: such as bulk density typically of 70–150 kg/cm3, an effective thermal conductivity of 0.014 W/(mK) at atmospheric. Commercial aerogel thermal insulators for building purposes have a thermal conductivity of around 0.014 W/(mK) at ambient temperature and are very little affected up to a temperature of 200°C [2].

Nanogel windows

Glazing systems have a huge impact on energy consumption, since the choice of glazing will determine the amount of heat gain and solar radiation entering the room and increase the cooling load inside the room. A well-established approach to heating and cooling energy saving is the application of advanced technology window glass with selective coatings.

Nanogel windows (with silica aerogel in the inter-space) is one of highly efficient windows due to their high thermal insulation coefficient (thermal conductivity of silica aerogel is as low as 0.010 W/mK) and light transmittance [2].

Aerogel is a silica-based, open-cell, foam-like material composed of about 4% silica and 96% air. The microscopic cells of the foam entrap air (or another gas if gas-filled), thereby preventing convection while still allowing light to pass. Aerogel has received research attention for its ability to be both highly transparent and insulating, making it one of a number of materials that are generically referred to as transparent insulation [5].

Silica aerogel, monolithic and granular translucent ones, can be used in order to obtain high-insulated nanogel windows. Nanogel windows are excellent in the thermal insulation of buildings because of the very low thermal conductivity of transparent or translucent silica aerogel. It is one of the lowest center of glass U-values was found (0.30 W/m2 K), seem to have the greatest potential for improving the thermal performance, daylight, and solar properties in the windows sector [2].

2- Energy Performance of Building Envelope

Building envelope plays a key role in building energy efficiency and in recent years has undergone a thorough review of its features and requirements to find technological solutions that can guarantee continuous adjustment of environmental flows in relation to climatic conditions and other factors [3].

The thermal energy performance of the building envelope is significant to achieve optimal performance of buildings. Moreover, researches have shown that building envelopes contribute more than 50% of the embodied energy distribution in major building elements in residential buildings; it also contributes approximately 50–60% of the total heat gain in buildings [1].

The building envelope constitutes a complex system of barriers and filters that regulate the flow of heat, solar radiation, air, and steam, and can also convert radiation into energy. Transfer of heat from the exterior to the interior of climate-controlled spaces and vice versa results in a significant loss of energy. Regarding the rate of heat transfers through the building envelope it is found to be related to the following important variables [6]:

1. Indoor and outdoor temperature;
2. Conductivity of the individual envelope components; and
3. The square footage of each of the envelope components.

Building envelope components has three important characteristics that affect their performance: their U-value or thermal resistance R-value; their thermal mass or ability to store heat (heat capacity) and their exterior surface finish (for example, light surface color reflects heat and dark surface absorb solar heat).

The energy efficiency of envelope systems can be improved with the following measures [7]:

- Controlling heat loss and heat gains through building materials; both opaque and transparent parts.
- Improve thermal insulation of walls, roofs and floors by using insulating materials or larger thickness.
- Controlling heat gains of transparent surfaces by using appropriate Window to Wall Ratio (WWR) and shading devices.

Thus, improvements in the thermal envelope of a building can produce large savings and improvements in the building energy efficiency. Improvements in the thermal envelope of a building can reduce heating loads by more than 30 %. Similarly, advances in window technology, such as improved glazing, can reduce the intake of passive solar heat by 75 percent and thus reduce cooling needs [8]. Enhancements may include improvements in installation, capitalizing on advances in the efficiency of windows and doors, improving the exchange of heat, and increasing the tightness of the building envelope, this paper is focusing only on thermal insulation materials and window systems

2-1- Specifying the building envelope parameters

Building envelope parameters could be sorted as building materials as basic elements (opaque parts, glazed parts, relation between opaque and glazed areas (window to wall ratio), and shading devices as auxiliary elements.

To specify the effect of building envelope on the energy conservation this paper investigates some of its design parameters, as shown in Figure 1, which affecting thermal performance.

The study involves examining the performance of the following elements through an empirical study to illustrate the potential of using Nano-based materials to improve the efficiency of the building envelope and reduce energy consumption:

2. Transparent materials used in the building envelope (windows and openings).

3. Thermal insulation materials.

Simulation process

Computer assistance (simulation process) was the more appropriate as it allowing the flexibility to implement and test various types of building materials with different properties to predict their effect on the building energy consumption.

In order to simulate the building energy performance the Energy Plus simulation tool was chosen. Energy Plus was developed from both the BLAST and DOE.2 programs.

This work is licensed under a Creative Commons Attribution 4.0 International License

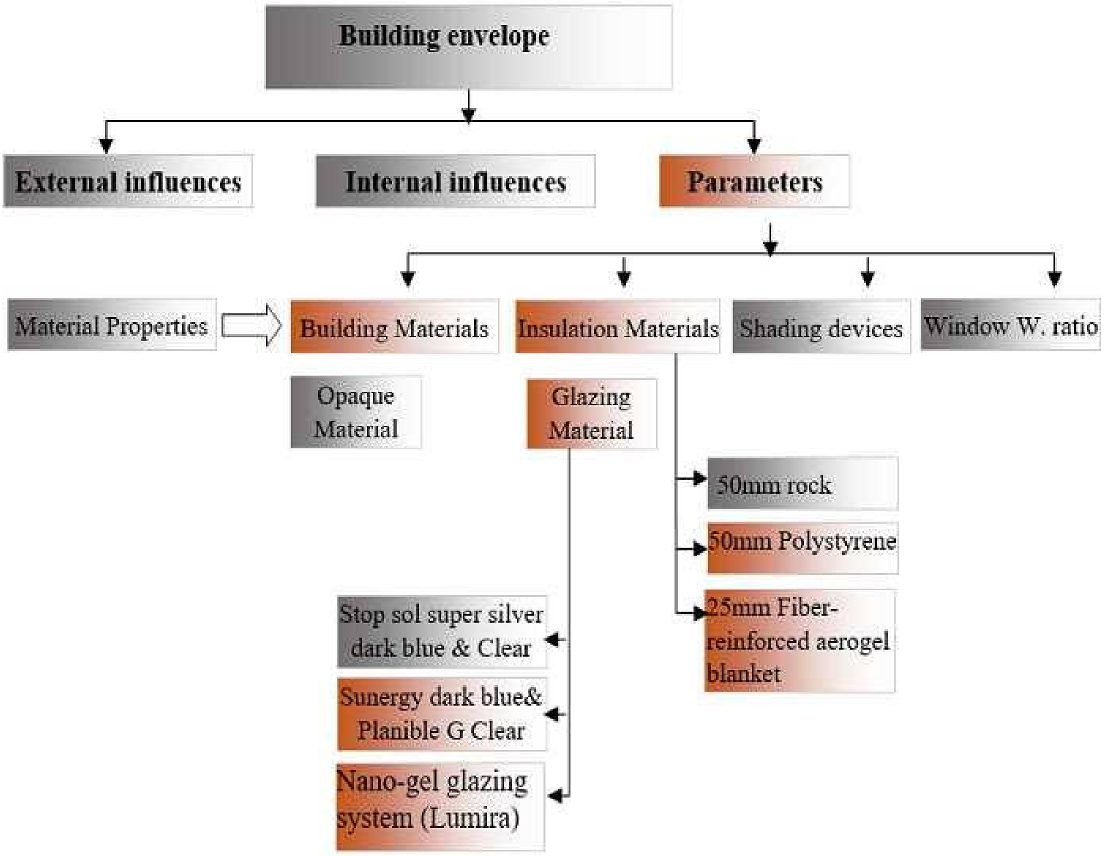


Figure 1: Investigated Building Envelope parameters (the researcher)

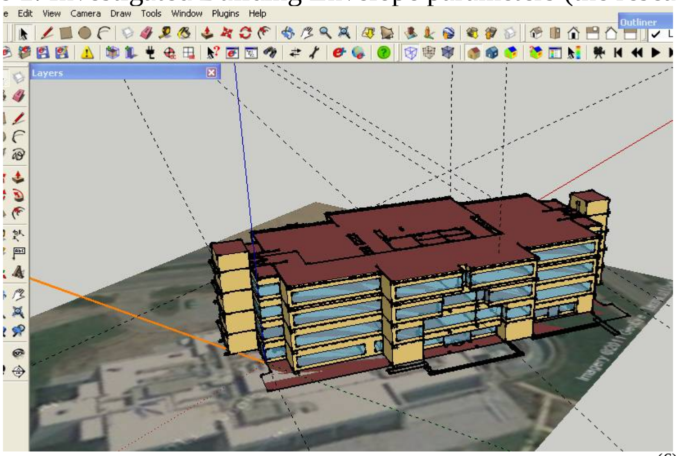


Figure 2: Building Geometry of the Energy plus Model [(6)]

2. Simulation tool

Euclid is derived from the open-source *Legacy Open Studio* extension originally developed by the National Renewable Energy Laboratory (NREL). Euclid is a free and open-source extension for Sketch-Up that makes it easy to create and modify the geometry inputs for building energy models [(9)]. It was used to model the building (case study). Because NREL no longer supports Legacy Open-Studio, Big Ladder Software has taken over maintenance, development, and support of the extension–now renamed as Euclid.

Just like its precursor, Euclid will continue to support reading and writing of Energy-Plus geometry in its native IDF format, but will also add new features and capabilities to read and write other energy model formats. Figure 2 represents a building geometry of Energy Plus model using Sketch Up.

<u>Scope of the Study</u>

The research conducted an empirical study aiming at indicate rates of heat gains through the building envelope and rates of savings energy consumption. This is done by comparing the energy consumption through the base case with traditional building materials for windows and thermal insulation and through the improved model using the nano-based building materials as shown in figure1.

2.1. The Base Case

The sample building for the study was Alaraby Bank, Smart Village, Egypt. This building has been investigated through a previous study conducted by the researcher with other applications. This sample was labeled as Base Case.

The base case has two construction types of external walls. There is rock wool insulation between the wall and the glass cladding in the first type. The second one is a 200 mm hollow cement brick wall and two plaster layers of both sides without insulation. Exterior windows composed of double glass system. The external panes (6mm panel thickness) are coated with special solar protection coating in their internal face (Stop sol silver dark blue), while the internal window panes are uncoated (clear glass) and with 8mm thickness.

The building is divided into twenty five Thermal zones. A "zone" is a *thermal,* not a *geometric,* concept. A “zone” is an air volume at a uniform temperature plus all the heat transfer and heat storage surfaces bounding or inside of that air volume [10].

Simulated Building Performance

The Base case was simulated by Sketch Up with Euclid as a plug in and Energy Plus program for a whole year. The simulation process was first used to analyze the heat gains and losses from different sources; the envelope (solar gains through windows, walls, and external infiltration), internal sources (Occupancy, electric equipments and general lighting. Reviewing annual rates of heat gains and losses (figure 3), shows that [6]:

- For building envelope, window heat gains are the dominant ones in all zones of the building in each orientation with different magnitudes.
- Solar gains comprise the main contribution of the envelope loads; mainly for their magnitude, particularly with the high WWR, since it reaches 50% in the south-west orientation, 40% in the south east orientation, and 50% in the north east orientation.
- The second contributor in envelope loads transfer is walls whose contribution differs between orientations.

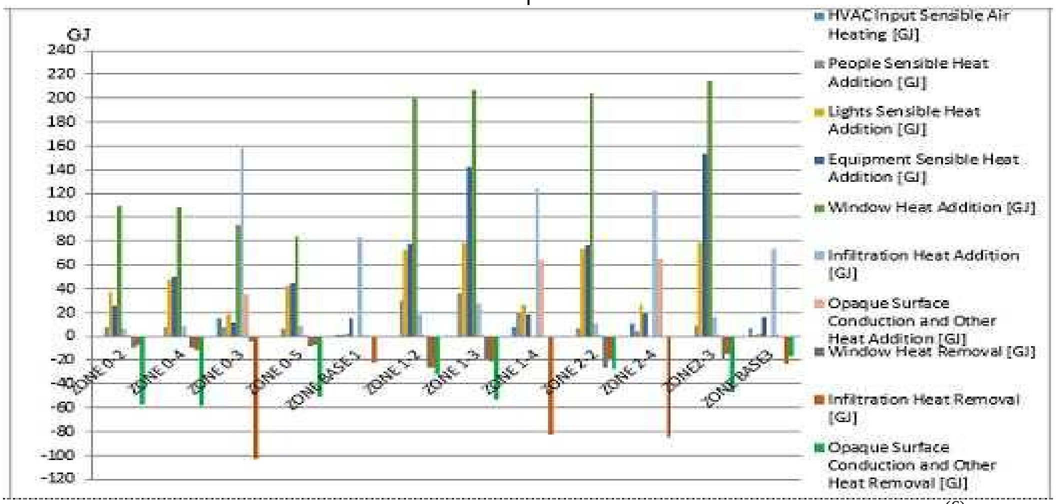


Figure 3: Annual heat gains and losses’ sources in the actual case zones [6]

3. Improved Case

Improved Case is actually a design enhancement of the Base Case with regard to the Nano-based building envelope materials (Fiber Reinforced Aerogel Blanket, as a nano-base thermal insulation, and Nanogel windows).

Improving the energy performance of buildings in this research has mainly focused on how the integration of nano-based materials (nano-base thermal insulation, nanogel windows) in the building envelope affecting building energy consumption.

3.1. Building insulation;

The paper investigates thermal insulation in two ways:

- Implementing a thermal insulation material with the opaque parts of the building to be a cavity wall of two layers of 120 mm hollow cement bricks, an in-between 50 mm rock wool fiber thermal insulation, and two plaster layers on both sides of the wall.
- Changing the used thermal insulation material (rock wool fiber, 50 mm thickness, 50 kg\m3 density, and thermal conductivity 0.05w/m-K, Firstly with polystyrene, 50 mm thickness, 30 kg\m3density, and 0.035w\m-k thermal conductivity, and secondly with using Nano-based thermal insulation material (Fiber-reinforced aerogel blanket, 5 mm thickness, 70-150 kg\m3 density, and thermal conductivity 0.014w/m-K

- Graphs shown in Table 2 represent Simulation results for the base case and the other investigated two models with different thermal Insulation materials (the materials which have the highest effect on building energy consumption), as follows:

First Case (base case);

Type 1; Hollow cement bricks (20mmcement

This work is licensed under a Creative Commons Attribution 4.0 International License

plaster, 250mm bricks, 50 mm rock wool thermal insulation and structure glazing).

Type 2; Hollow Cement bricks (20mmcement plaster, Sandwich 120mm hollow cement brick wall, with 50 mm rock wool thermal insulation, 20 mm cement plaster)

Table1: Comparison between aerogel and traditional insulating materials [3]

Insulating Material	Conductivity (w/m-k)	Thickness (m)	R (m^2-k/w)	Density (kg/m^{3})	C_p (j/kg-k)
Fiber Reinforced Aerogel Blanket	0.013	0.01		70-150	1000
Expanded Polystyrene	0.034	0.0262	0.1123	2528.00	1450
Rockwool fiber bonded	0.050	0.0500	1.000	50.00	750.00

Second Case;

Type 1; Hollow cement bricks (20mmcement plaster , 250mm bricks, 30 mm polystyrene insulation and structure glazing)

Type 2; Hollow Cement bricks (20mmcement plaster, Sandwich 120mm hollow cement brick wall, with 30 mm polystyrene insulation, 20mmcement plaster)

Third Case;

Type 1; Hollow cement bricks (20mmcement plaster , 250mm bricks, 5 mm fiber-reinforced aerogel blanket and structure glazing)

Type 2; Hollow cement bricks (20mmcement plaster, Sandwich 120 mm hollow cement brick wall, with 5 mm fiber-reinforced aerogel blanket, 20mmcement plaster)

Table 2: A comparison between cooling energy consumption through the base case and the investigated thermal insulation materials

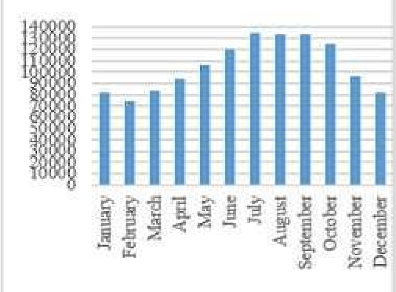
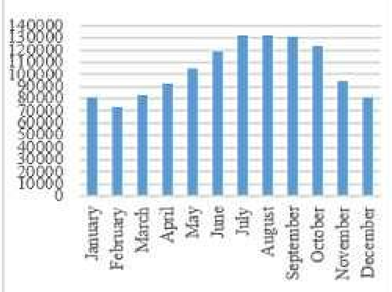
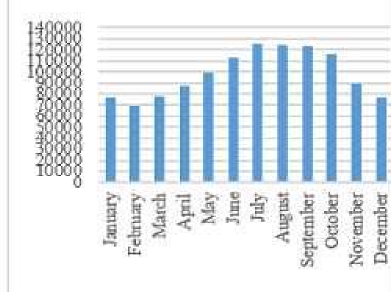
Cooling loads for **Existing with 50mm Rockwool**	Cooling loads through **model Advanced glazing system** (Sunergy Glass+planible	Cooling loads through **model with Nano-gel windows (Lumira)**
		
	2.15%Reduction in Cooling energy consumption	7.41%Reduction in Cooling energy consumption

Table 3: Characteristics of typical window panels studied for the building [11]

Structure		Light Properties		Thermal Properties			European U-Value	American Standards		
Coating in position 3	Thickness	LT %	LR (Ext) %	EA %	SF	SC	W/m².K U value	Summer U value W/m².K	Winter W/m² W/m².K	RHG W/m²
Planibel G	4mm	82	11	19	73	0.84	3.8	3.64	4.22	558
	6mm	81	11	22	71	0.82	3.7	3.62	4.17	545
	4-12Ar-4	74	17	24	73	0.83	1.6	2.13	1.94	541
Sunergy Dark Blue	6mm	40	6	65	38	0.44	4.1	4.59	4.59	327
	8mm	35	6	74	35	0.39	4.1	4.54	4.60	300

K 25/60 Series Profillt	Uninsulated	LUMIRA® AEROGEL Panel* 16 mm (CLEAR)	LUMIRA® AEROGEL Panel* 25mm (Clear)
U Value (Glass Only)	0.49	0.21	0.19
Light Transmission	70%	50%	38%
Solar Heat Gain Coeff. (SHGC) (NFRC 200)	0.63	0.42	0.31
Coeff. (STC) - (E 90)	42	44	44
Condensation Resistance Factor (CRF) (AAMA 1503)	G 70 F 60	G 79 F 60	G 79 F 60

3.2. Glazing Materials;

In the building studied here, exterior windows composed of double glass system. The external panes (6mm panel thickness) are coated with special solar protection coating in their internal face (Stop sol silver dark blue), while the internal window panes are uncoated (clear glass) and with 8mm thickness. The paper investigates other types of the glass as follows:

- Changing the used glazing system (Stop sol silver dark blue 6mm+ 13mm air + clear glass 8mm), Firstly with (Sunergy Glass 6mm + 13mm air + planible G clear 6mm), and secondly with using Lumira Aerogel panels 25mm*, the thermal performance of these systems are as shown in Table 3

- Graphs shown in tables 4 represent Simulation results for the base case and the other investigated two models with different structure glazing systems as follows:

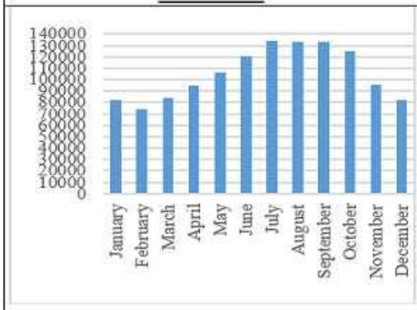
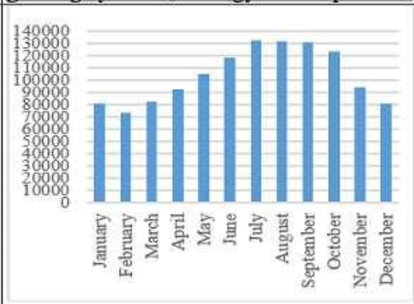
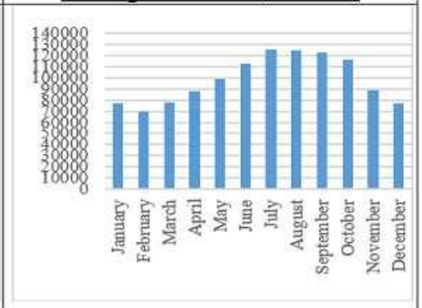
<u>First case;</u>
Type 1; Hollow cement bricks (20mmcement plaster , 250mm bricks, 50mm rock wool thermal insulation and <u>advanced glazing system consists of (Sunergy Glass 6mm + 13mm air + planible G clear 6mm).</u>
Type 2; Hollow cement bricks (20mmcement plaster, 250mm bricks, 20mmcement plaster)
<u>Second Case;</u>
Type 1; Hollow cement bricks (250mm bricks, 50mm rock wool thermal insulation and Nano-gel glazing system (Lumira).
Type 2; Hollow cement bricks (20mmcement plaster, 250mm bricks, 20mmcement plaster)

3.3. Combined Nano-based Building materials

Through this part the research investigates the effect of implementing the previous nano-based building envelop materials (Aerogel as a thermal insulation material – nanogel window system (Lumira)), which studied separately through the previous part, all together to determine their influence on building energy consumption.

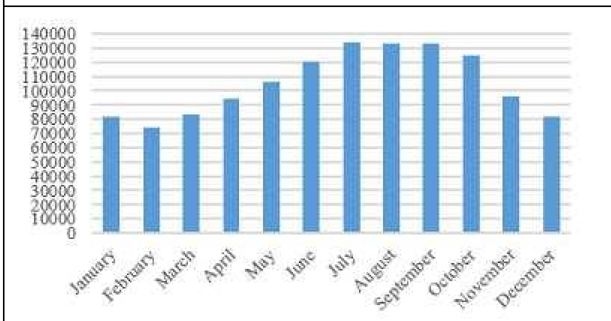
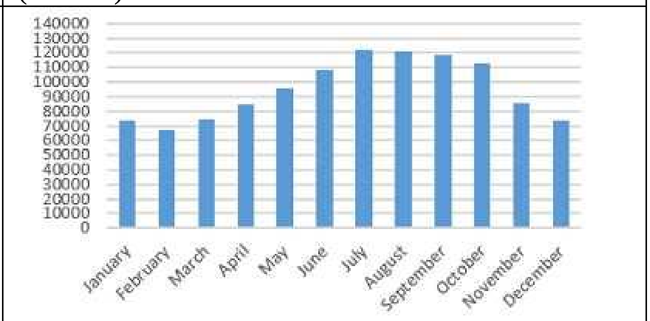
Graphs shown in tables 5 represent Simulation results for monthly cooling electricity consumption through the base case and the improved model with combined nano-based building materials (the materials which have the highest effect on building energy consumption), as follows:

Table 4: A comparison between cooling energy consumption through the base case and the investigated models with different structure glazing systems

Cooling loads for **<u>Existing with 50mm Rockwool</u>**	Cooling loads through **<u>model Advanced glazing system</u>** (Sunergy Glass+planible	Cooling loads through **<u>model with Nano-gel windows (Lumira)</u>**
		
	2.15%Reduction in Cooling energy consumption	7.41%Reduction in Cooling energy consumption

<u>Improved model;</u>
Type 1; Hollow cement bricks (250 mm bricks, <u>5 mm fiber-reinforced aerogel blanket</u> and Nano-gel glazing system (Lumira)
Type 2; Hollow cement bricks (20 mm cement plaster, Sandwich 120 mm hollow cement brick wall, with <u>5 mm fiber-reinforced aerogel blanket</u>, 20 mm cement plaster)

Table 5: A comparison between cooling energy consumption through the base case and the improved models with the nano-based building materials

Cooling loads for **<u>Existing (base case)</u>**	Cooling loads through **<u>improved model</u>** <u>5 mm fiber-reinforced aerogel &</u> Nano-gel glazing system (Lumira)
	
	10.78 % Reduction in Cooling energy consumption

This work is licensed under a Creative Commons Attribution 4.0 International License

Total Loads Analysis

It is important to mention that internal loads (occupants, electrical equipments, and internal lights) are constant parameters in the simulation process.

Reviewing simulation results for each element separately, (Insulation materials, glazing system), it is found that the effect of each element is very low on both; total energy consumption, particularly the building cooling loads as follows:

- 30 mm polystyrene insulation: resulted in 1.62% reduction in total energy consumption, and 2.38% reduction in cooling energy consumption.
- 5 mm fiber-reinforced aerogel blanket: resulted in 2.17% reduction in total energy consumption, and 3.15% reduction in cooling energy consumption.
- Structure glazing; Sunergy Glass 6mm + 13mm air + planible G clear 6mm: resulted in 1.61% reduction in total energy consumption, and 2.70% in cooling energy consumption.
- Nano-gel glazing system (Lumira): resulted in 4.93% reduction in total energy consumption, and 7.41% in cooling energy consumption.
- The graphs illustrate that there is a slight reduction in energy consumption till through the third case which contains the nano-based insulation materials, and nanogel glazing system. The reduction in total energy consumption through this case reaches 7.42% (216479 KWh) and 10.78% (137544 KWh) in cooling loads.

Conclusion

- Nanotech research is crucial in helping to identify methods to make buildings more environmentally friendly, since the huge progress in material science according to the nanotechnology revolution provides numerous of the nano-based building materials which have a high influence on the building energy efficiency comparing to the traditional ones. Due to the need to reduce building energy consumption, it’s important to investigate the integration of these materials to achieve more energy reductions.
- The paper investigated the building envelope energy performance as a main factor affecting the building energy consumption. For building materials (transparent parts) and thermal insulation of building envelope, the paper investigated the effect of using the nano-based materials on the building energy consumption comparing to the traditional materials through a simulation process as follow:

Two approaches were adopted in testing these materials:

1-Sensitivity to individual material;

2- Combined materials

- This comparison between the traditional building materials and the nano-base materials, represent in fiber-reinforced aerogel blanket as a nano-based thermal insulation and Nano gel windows, is conducted to discover the difference in energy consumption between the two cases to determine the effect of using these new materials on the building energy efficiency. It was found that, there is a considerable reduction in the total energy consumption reaches 7.42% (216479 KWh) and 10.78% (137544 KWh) in cooling loads as a result to implementing the nano-based building materials for these two positions.
- It is concluded that by using the Nano-based building materials for the all parts of the building envelope, the opaque parts, coatings and so on will result in a high energy reductions which consequently reduce the running cost of the building and on the other hand reduce the harm effect on the environment.

References

1. Ahmed Rashwan, Osama Farag, Wael Seddik Moustafa, Energy performance analysis of integrating building envelopes with nanomaterials, International Journal of Sustainable Built Environment, 2013
2. with nanomaterialsF. Pacheco-Torgal, M. V. Diamanti, A. Nazari and C-G. Granqvist, Nanotechnology in eco efficient construction, materials, processes and applications, second edition, Elsevier Ltd, 2019
3. Marco Casini, Smart Buildings, Advanced Materials and Nanotechnology to Improve Energy-Efficiency and Environmental Performance, Elsevier Ltd., 2016
4. F. Pacheco Torgal, Cinzia Buratti,Siva Kalaiselvam, Claes-Göran Granqvist, Volodymyr Ivanov, Nano and Biotech Based Materials for Energy Building Efficiency, Springer, 2016
5. WINDOWS for high performance commercial buildings, https://www.commercialwindows.org/adv_glass.php last access 21-1-2021
6. Elbony A. Fatma, Building Management systems as an Approach for Energy Conservation With special reference to Buildings in Cairo, Ain Shams University,

Doctor of Philosophy, 2013
7. Wayne C. Turner & Steve Doty, ENERGY MANAGEMENT HANDBOOK, Six edition, Fairmont Press, Inc, 2006
8. Charles P. Ries, Joseph Jenkins, Oliver Wise, Improving the Energy Performance of Buildings, technical report, RAND Corporation, 2009
9. IBPSA, International Building Performance Simulation Association, USA, https://www.ibpsa.us/news/euclid-extension-sketchup-now-available last access 21-1-2021
10. ENERGYPLUS, Getting Started with Energy Plus, Basic Concepts Manual, US Department of Energy, 2010.
11. https://www.tgpamerica.com/resources/product-downloads/fact-sheets/doc/pilkington-profilit-insulation-fact-sheet.pdf

This work is licensed under a Creative Commons Attribution 4.0 International License