

## Evaluating Thermal Insulation Materials to Enhance Energy Performance in Residential Buildings: A Comparative Study Using Design Builder

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### Abstract

Good insulation is one of the most important issues to make buildings more energy-efficient and friendly to the environment. There are many different insulation materials, making it difficult to compare their efficiency, therefore this paper introduces a comparative study of some thermal insulation materials which are employed to enhance the energy efficiency of residential buildings in hot dry environments. Design Builder program is used to illustrate heat transfer, energy demand, and comfort levels in different thermal insulation conditions. A group of insulation materials is selected to examine their efficiency, such as expanded polystyrene (EPS), polyurethane foam (PU), rock wool, and aerogel, depending on their thermal conductivity, thickness, and impact on the annual energy required for cooling a space. The results of the simulation point out that the selection of insulating material has a significant effect on energy efficiency. Aerogel used the least energy and achieved the greatest reduction in cooling load. Rock wool was the most cost-effective choice, but it was just average in terms of efficiency. The results of the simulation give architects and engineers vital information on how to choose the best insulation solutions for long-term energy management, and how to provide comfortable internal environment with low energy consumption.

**Keywords:-** Thermal insulation materials, Building energy performance, Sustainable building envelope, Energy efficiency, Heat transfer simulation, Cooling load reduction.

### 1. Introduction:

Improving the energy performance of buildings is a vital issue, increasingly significant in the face of global environmental and economic challenges, especially in countries with warm climates [1]. Residential buildings consume a lot of energy, which makes the reliance on non-renewable energy sources greater. This dependence is bad for the environment since it causes more emissions and climate change. The best way to minimize energy use in buildings is to improve their thermal insulation. Good insulation reduces the amount of heat that travels between the structure envelope, then lowers the demands of heating and cooling. Lots of studies have been done on the energy performance and thermal properties of various types of insulation. There is a significant difference in thermal conductivity, environmental impact, cost, and durability [2]. Different types of insulation materials are available on the market; however, it is difficult to recognize how they actually affect energy performance. Therefore, it needs to precise and comprehensive research. This study aims to compare varied types of thermal insulation materials to determine their effectiveness in improving the energy use in residential building.

Simulation program Design Builder and advanced design will be used in this study. A traditional house in the Iraqi environment has been selected in this paper to determine the most effective materials in minimizing energy use and improving the thermal comfort for occupants, depending on simulating the energy efficiency. The impact of thermal insulation materials on energy efficiency during summer, will be examined by creating a precise 3D model developed with Design Builder software, to analyze the effects of various variables on energy use. The findings aim to provide trustworthy data for researchers to improve building designs in Iraq, leading to high and long-lasting energy efficiency. The study also supports the environmental issues by enhancing energy efficiency in Iraq's construction sector, promote sustainability, conserve natural resources, and reduce energy-related costs.

## 2. Literature review:

It is essential to assess energy consumption in residential buildings, especially in arid regions like Iraq, in order to reduce the reliance on outdated and inefficient mechanical cooling systems. Moreover, the buildings envelopes do not play a good role in maintaining heat inside or outside the building. Therefore, the residential sector consumes a significant amount of energy. This may lead to an increased awareness of the importance of employing the thermal insulation systems to lower heat gain, which will decrease energy use for cooling and provide thermal in buildings located in hot climates.

### The Strategic Significance of Insulation:

Numerous studies have demonstrated that adding good thermal insulation systems reduces the amount of energy required for cooling buildings. [3] found that the effective thermal insulation can reduce household energy consumption by up to 40 under hot and dry conditions. The thermal insulation helps maintain a stable indoor temperature according to [4]. In addition, using less energy results in lower greenhouse gas emissions during electricity generation. Therefore, thermal insulation may be considered a comprehensive solution a comprehensive solution encompassing environmental sustainability, technological efficiency, and economic benefits.

### 2.2. Insulation Materials: Traditional vs. Sustainable

Choosing insulating materials for the construction industry, depends on many factors, such as their thermal conductivity, durability, environmental impact, and cost. Some of the most prevalent conventional materials are rock wool, expanded polystyrene (EPS), and polyurethane foam. These materials are easy to find and use. Researchers and others who work in the building industry are, however, growing more interested in eco-friendly insulation materials like cork, natural fiber boards, and other bio composites. [5] said that when picking materials, you should think about how easily they are to put together, how well they will work over time, how much they will cost over their lifetime, and how the weather would influence them.

### 2.3. Optimizing the Performance of Thermal Insulation

When developing a good thermal insulation plan, the key considerations are reducing costs, maximizing energy savings, and minimizing environmental impact. [6] emphasized the importance of having a comprehensive strategy to introduce the innovative solutions to balance

economic and environmental sustainability, especially in developing countries with hot climates and limited financial resources.

#### **2.4. The Role of Simulation Tools in Performance Evaluation**

Advanced simulation software for studying how to make buildings more energy efficient has become an important tool for figuring out what kinds of building materials to use and how to design buildings. Design Builder, which runs on the Energy Plus engine, is one of the best simulation programs for testing how well different thermal insulation materials and design scenarios work before they are put into use. These methods have been utilized to investigate several design alternatives across diverse meteorological conditions and occupancy patterns, thereby avoiding the costs associated with extended field experiments [7].

#### **2.5. Applications in the Iraqi Context**

Many studies have demonstrated that better insulation systems in Iraq can help people use less energy. Because Baghdad is hot, [8] used a "structural design" simulation tool to show that a well-insulated design saves more than 30% of the energy used each year. Despite these encouraging findings, energy-efficient building solutions are still not widely used. A local study conducted by [9] indicated that most homes in Iraq lack thermal insulation. [10] assert that the persistent utilization of low-energy-efficient residential buildings in Iraq is mostly, due to the lack of stringent rules and clearly established thermal performance standards.

### **3. Research Gaps**

Despite there is extensive research on thermal insulation worldwide, such studies remain limited in Iraq. Numerous residential buildings have been constructed without consideration for energy consumption or thermal retention, This may be due to limited awareness of environmentally sustainable design. Therefore, conducting comprehensive comparative analyses is essential to evaluate the effectiveness of various insulating materials under the hot and dry climate conditions characteristic of Iraq. These analytical studies will contribute to the development of national building standards that make homes environmentally friendly.

### **4. Research Methodology:**

#### **4.1. Research Approach**

A quantitative experimental approach depending on computer simulation was employed in this study. The Design Builder software was utilized to evaluate energy performance in residential buildings. The major aim was to assess the impact of various types of thermal insulation materials in minimizing energy consumption and improving indoor comfort, especially in the hot and dry climate of Iraq.

#### **4.2. Research Design**

In order to compare different insulation materials accurately, a quasi-experimental approach was adopted. To idealize the most typical type of house in residential neighborhoods in Iraq, a three-dimensional model of a typical house was created. Afterward, various insulation materials were applied to the same model, by keeping the same occupancy patterns, orientation, and internal heat gains. Multiple simulations were conducted, allowing us to directly identify differences resulting from the use of specific insulation materials.

### 4.3. Research Tools

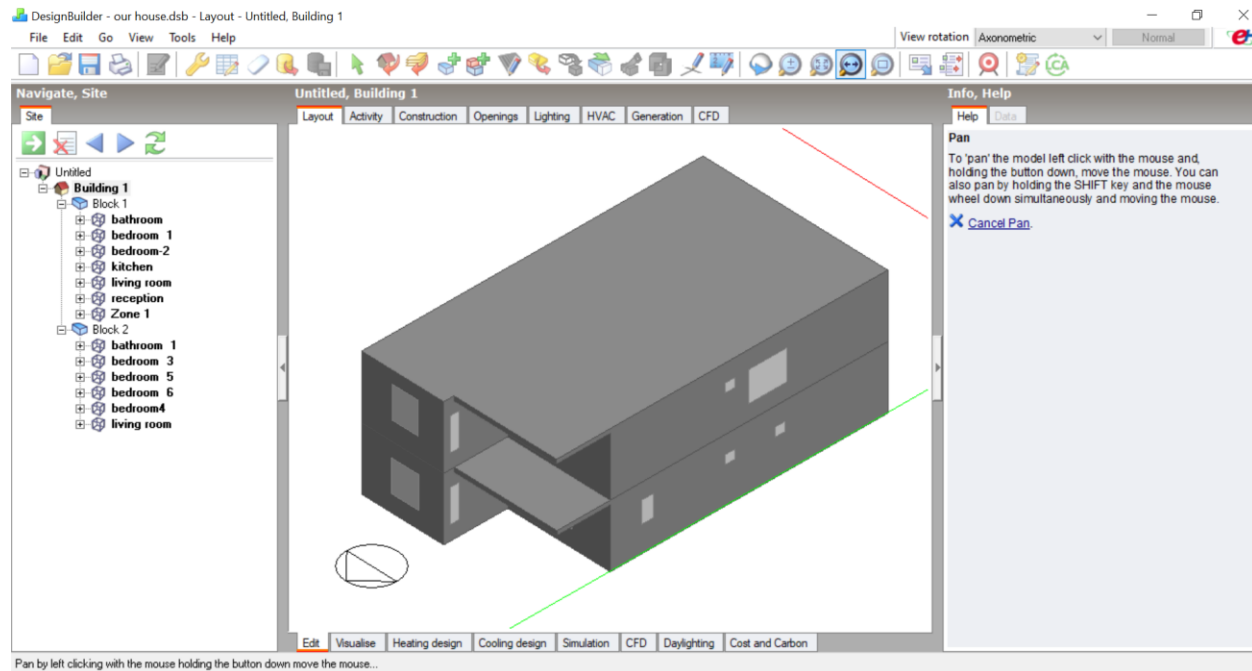
Design Builder software (version 6.1.0.0006), which is based on the Energy Plus thermal analysis engine, was used to perform the simulation. The reason of choosing this software is because of its accuracy and its ability to predict changes in building temperature and energy consumption. The simulation input data and the physical properties of the insulating materials were obtained from reputable scientific sources and published studies.

### 4.4. Insulating Materials Analyzed:

Several insulation materials have been selected because of their wide use in both the Iraqi and global markets. Common insulation materials are Expanded polystyrene (EPS) and rock wool with a thermal conductivity respectively ranging from 0.040–0.030 W/m·K, and 0.045–0.033 W/m·K [11]. The broadly use of these materials due to their abundance, low cost, and well performance in heating [9]. Although the expanded polystyrene is characterized by high compressive strength and moisture resistance, it is harmful to the environment because it is derived from non-renewable resources, [12]. Robust polyurethane foam is considered an excellent insulator with thermal conductivity ( $\lambda \approx 0.028\text{--}0.022$  W/m·K) and it has been proven to appreciably minimize energy use in buildings in hot climates [13]. These materials are still considered as the most popular choice, despite issues related to sustainability, aging, and fire safety [14]. Recently, research has concentrated on new insulation methods that aim to achieve very low thermal conductivity and acceptable aging. Aerogel materials have been tested as coverings or layers of envelope. They feature their porous nanostructure and excellent insulation ( $\lambda = 0.018$  W/m·K). Using this type of insulation can lower energy consumption by 30% to 40% annually compared to traditional insulation, [15]. This advanced material holds considerable promise for decreasing energy consumption, but it remains not broadly applied because it is expensive, difficult to install, and lack of information on its long-term effectiveness [16].

### 5. Building Model:

A three-dimensions virtual model of a two-story house with a total built-up area of 300 square meters has been established. It includes several standard rooms, such as the living room, reception, bedrooms, kitchen, and bathroom. The design takes into account typical construction practices in Iraq, such as the materials used for finishing, the windows, and the direction of the facade (Fig. 1).



**Fig. 1: A model of a residential building with a floor area of 300 square meters, made by a Design Builder.**

### 5.1.The Climate Zone:

Babylon was chosen as a representative climate site due to its hot, dry climate and high summer temperatures, which pose challenges for effective thermal insulation.

### 5.2.The Studied Variables:

Independent Variable: The kind of thermal insulating material. Dependent Variables: Total cooling in July and August (kWh), indoor temperature ( $^{\circ}\text{C}$ ), and heat transfer coefficient (U-Value).

### 5.3. Research Limitations:

The study depends on digital simulation rather than real-world tests. Economic concerns, including material costs and installation expenses, have not been examined. The study exclusively examines residential structures in arid, hot climates, neglecting cold or humid regions.

## 6. Results and Analysis:

Three main indicators were used to assess the findings from thermal simulations executed with Design Builder software to evaluate the efficacy of various thermal insulation materials in a standard residential structure situated in a hot and arid region (Babylon, Iraq). These indicators are: cooling demands during the summer season, indoor temperature, and the (U-value). The aim of the evaluation is to highlight the most effective insulating materials employed in the construction to decrease the energy consumption and achieving thermal comfort. Table (1) illustrates the amount of energy used in each scenario during the summer days.

**Table (1): energy used throughout summer days for each scenario.**

Type of Insulation Material	Energy Consumption (kWh)	Reduction Percentage Compared to Reference Case (%)
Without Insulation (Reference Case)	27,500	
Rock Wool	17,950	34.7%
Expanded Polystyrene (EPS)	16,800	38.9%
Polyurethane Foam (PU)	15,600	43.3%
Nano Insulation (Aerogel)	13,750	50%

Analysis: As shown in table 1, the nanostructured insulation material (aerogel) achieved the lowest energy consumption rate, with approximately a 50% reduction in energy use, followed by polyurethane foam. Rock wool showed acceptable performance with a limited difference compared to polyurethane foam..

Simulation results indicated that using insulation materials led to stability in indoor temperatures within the building, especially during the summer, enhancing thermal comfort. Table (2) shows the annual average indoor temperatures in air-conditioned rooms:

**Table (2): Annual average indoor temperatures in air-conditioned rooms**

Type of Insulation Material	Average indoor temperature (°C)
Without Insulation (Reference Case)	35.4
Rock Wool	30.1
Expanded Polystyrene (EPS)	28.3
Polyurethane Foam (PU)	27.5
Nano Insulation (Aerogel)	26.7

Analysis: It is noted that the best thermal control was achieved using nanomaterial insulation, where the temperature decreased by 8.7 degrees compared to the reference case, which directly reflects on reducing the need for cooling.

Heat transfer coefficient (U-value):

The U-value for a typical external wall was calculated in each case, and the table (3) shows the recorded values by Design Builder and the theoretical values calculated according to the standard thermal equation, [1,eq.(17)]:

$$U\text{-Value} = \frac{1}{R}$$

$$R_{\text{total}} = R_{\text{si}} + \sum \left( \frac{d}{\lambda} \text{ for all layers} \right) + R_{\text{se}}$$

D = Thickness of layer (m)

$\lambda$  = Thermal conductivity of the material (W/m·K)

$R_{\text{si}} = 0.13$  Internal surface resistance (m<sup>2</sup>·K/W)

$R_{se} = 0.04$  external surface resistance ( $m^2 \cdot K/W$ ).

**Table (3): U-values by design builder and the theoretical values calculated according to the standard thermal equation.**

Wall	Rsi	Rse	$\sum d/\lambda$ for all layers	R. total	U-value 1/R total	U-value By design builder
Without insulation material	0.13	0.04	$0.02/1.4+0.25/0.7+0.2/0.16$	1.77	0.565	0.561
Wall with EPS	0.13	0.04	$0.02/1.4+0.05/0.035+0.25/0.7+0.2/0.16$	3.2	0.312	0.312
Wall with Rockwool	0.13	0.04	$0.02/1.4+0.05/0.033+0.25/0.7+0.2/0.16$	3.3	0.3	0.35
Wall with (PU Foam)	0.13	0.04	$0.02/1.4+0.05/0.028+0.25/0.7+0.2/0.16$	3.55	0.28	0.28
Wall with Aerogel	0.13	0.04	$0.02/1.4+0.05/0.018+0.25/0.7+0.2/0.16$	4.06	0.218	0.247

The simulation results confirmed the importance of thermal insulation in reducing energy consumption and improving thermal comfort in homes.

By comparing the performance of the indicators, it can be observed that modern materials with high thermal resistance, such as aerogel and polyurethane foam, perform significantly better than traditional materials like rock wool, and EPS materials especially in harsh climates such as Iraq. Therefore, selecting appropriate insulating materials significantly contributes to reduce energy consumption, especially in hot regions. Besides, the results of U-value showed the accuracy of the simulation program used in this study, as the U-values calculated using the Design Builder program were noticeably close to the theoretical values calculated using the standard thermal equation.

## 7. Results Discussion:

This part of the research clarifies the results of thermal simulation in terms of the three indicators. It also highlights to what extent the results resemble or differ from previous studies, and how the research contributed to fill gaps in current knowledge.

The simulation results showed that energy consumption during the summer season decreased at varying rates, especially high-efficiency options such as aerogel and polyurethane foam, due to the ability of these materials to limit heat leakage through the walls. Consequently, reliance on mechanical cooling systems is reduced, thereby lowering electricity consumption. These results are consistent with the study conducted by [5], which indicates that using high-efficiency insulating material can reduce energy consumption by about 40% in hot climates.

In term of maintaining stable inner temperatures can be seen that nano insulation (aerogel) is the best option for reducing energy consumption, when comparing different insulation materials, because it has very low thermal conductivity and low thermal mass. It was followed by traditional materials such as expanded polystyrene (EPS) and rock wool which are relatively effective, because of their limitations to reduce thermal loads compared to contemporary materials. According to [18], the performance levels of different types of insulation were recorded at relatively high rates of 20–30%. The most notable findings are the improvement of thermal comfort inside the building, and maintaining stable indoor temperatures, particularly during hot summer days. Providing a high level of thermal comfort for occupants without reliance on mechanical system, supports the principles of environmentally friendly architecture, which depends on passive strategies to achieve a comfortable indoor environment. According to the third indicator (U-value) the effectiveness of insulation materials is one of the most important factors in reducing heat leak through the external wall in a well-designed building envelope, thereby reducing energy consumption in buildings. Accordingly, the results of the study align with the recommendations of ASHRAE and IECC, which stated that the essential factor to design low-energy buildings is improving the performance of the building envelope.

According to previous studies in this field, a large amount of electricity is consumed by residential sectors, especially in summer days. Depending on the research findings the thermal insulation materials can maximize the efficiency of the building. Consequently, policies should encourage people to use thermal insulation. In order to bridge the scientific gap in terms of the insulation materials in Iraqi buildings, this study employed Design Builder program in assessing the effects of insulation materials, and to raise awareness of the importance of thermal insulation in buildings, thereby achieving environmentally friendly buildings that align with sustainability principles. It also provided a practical side that lets designers and planners choose insulating materials based on exact numbers instead of just picking them at random. It is important to note that there are some limitations that could make it hard to generalize the results. For example, the study only used simulations and did not check them in the field; it only looked at one model of building and did not look at the variety of residential models; and it only looked at thermal performance and did not look at the deeper economic or environmental issues.

## 8. Conclusions and Recommendations:

Final thoughts Thermal simulations with Design Builder software and a study of how well different types of thermal insulation worked in a home in Iraq's hot and dry climate led to the following conclusions:

1. The study revealed that utilizing thermal insulation materials can cut energy use by 34% to 50% compared to buildings that aren't insulated.
2. Modern materials are better: Aerogel and Polyurethane Foam are two examples of high-tech materials that worked better than others in terms of thermal performance and lower U-Value. It can be considered the best choice for extreme climatic conditions..
3. Thermal insulation materials work to improve the thermal comfort of occupants by reducing the temperature of the indoor space during peak hours of summer days, without relying on mechanical systems.

4. This study confirmed the usefulness of simulation programs such as Design Builder: through the results, it can be observed that it is an effective tool in analyzing building performance in terms of improving thermal comfort and reducing energy consumption, as well as assisting architects in making design-related decisions.

### 8.1. Recommendations:

1. Architects are encouraged to use effective thermal insulation as an essential part of designing environmentally friendly buildings, especially in hot climates like Iraq. In addition, employing simulation tools such as Design Builder in the early design stages helps make accurate decisions based on scientific evidence.
2. Establishing policies and conditions for project owners regarding the use of thermal insulation materials. The absence of thermal insulation is considered illegal according to modern building regulations that take sustainability into account, in addition to encouraging them by offering facilities such as tax exemptions or other incentives.
3. Expanding the scope of research to include different types of buildings such as hospitals, schools, and universities, to raise awareness about the benefits of thermal insulation materials from an environmental and economic perspective.
4. Auditing the research results based on simulation programs through field visits by carrying out actual measurements in existing buildings and comparing them with the simulation results.

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## تقييم مواد العزل الحراري لتعزيز أداء الطاقة في المباني السكنية: دراسة مقارنة باستخدام برنامج Design Builder

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### الخلاصة

العزل الجيد هو من أهم القضايا لجعل المباني أكثر كفاءة في استخدام الطاقة وصديقة للبيئة. هناك مواد عزل متنوعة وكثيرة يصعب اختيارها وتمييز كفاءتها، لذلك يقدم هذا البحث دراسة مقارنة لبعض مواد العزل الحراري التي تُستخدم لتحسين كفاءة الطاقة في المباني السكنية في البيئات الحارة والجافة. يتم استخدام برنامج Design Builder لتوضيح كيف تنتقل الحرارة، وكمية الطاقة المطلوبة، ومستوى الراحة في ظروف عزل حراري مختلفة. تم اختيار مجموعة من مواد العزل لفحص كفاءتها، مثل البوليسترين الموسع (EPS)، ورغوة البولي يوريثان (PU)، والصوف الصخري، والأيروغيل، اعتمادًا على الموصلية الحرارية، والسّمك، وتأثيرها على الطاقة السنوية المطلوبة لتبريد المكان. وتشير نتائج المحاكاة إلى أن اختيار مادة العزل له تأثير كبير على كفاءة الطاقة. حيث استخدم الأيروسيل أقل كمية من الطاقة وقلل العبء التبريدي إلى الحد الأكبر. كان الصوف الصخري الخيار الأكثر فعالية من حيث التكلفة، لكنه كان متوسطًا فقط من حيث الكفاءة. تقدم نتائج المحاكاة معلومات حيوية للمعماريين والمهندسين حول كيفية اختيار أفضل حلول العزل لإدارة الطاقة على المدى الطويل، وكيفية توفير بيئة داخلية مريحة مع استهلاك منخفض للطاقة.

الكلمات الدالة: - مواد العزل الحراري، أداء الطاقة في المباني، غلاف المبنى المستدام، كفاءة الطاقة، محاكاة انتقال الحرارة، تقليل حمل التبريد.