The thermal and energy performance comparison of extruded polystyrene foam insulation for an apartment building in different climate zones, Egypt

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Abstract- The energy sector continually grapples with formidable challenges, particularly in nations characterized by burgeoning populations, where the construction industry faces mounting pressure to curtail energy consumption. Among the influential factors impacting a building's energy usage and environmental building performance, thermal insulation materials stand out prominently. Consequently, this research selected a residential building, situated in diverse climatic conditions, to assess the implications of applying thermal insulation materials to the building's envelope on indoor thermal comfort and energy consumption, both in the current period and in the context of climate changes. Utilizing Design Builder software, an apartment was simulated for three major climate zones: semi-arid, Mediterranean, and arid regions. This assessment encompassed an evaluation of indoor thermal comfort and energy consumption, considering the existing conditions as the base case, and contrasting them with alternative scenarios. The principal findings derived from this study affirmed that the optimal solutions across all climatic zones effectively balanced the twin objectives of energy reduction and improved thermal comfort. The results underscored the significance of a complete wall construction composed of red brick with an additional layer of extruded polystyrene (XPS) thermal insulation as a pivotal strategy for diminishing heat gains and extending thermal comfort in all three climatic conditions. In the optimal scenario, the thermal comfort period increased by 34.9%, 21.9%, and 33.2% in Cairo, Alexandria, and Aswan, respectively. Furthermore, this approach achieved a noteworthy energy savings of 21.7% in Aswan, representing the highest energy conservation ratio when compared to Cairo (13.8%) and Alexandria (19.9%).

Keywords- Energy Consumption, Residential Buildings, Thermal Comfort, Thermal Insulation, Extruded Polystyrene.

I. INTRODUCTION

The global energy sector is currently grappling with formidable challenges, and energy efficiency in residential buildings has emerged as a prominent research focus for scientists worldwide. Egypt ranks the largest consumer of oil and natural gas in Africa, accounting for approximately 20% of total petroleum consumption and 40% of dry natural gas consumption on the continent. Egypt's oil consumption exceeds its domestic production capacity [1]. Furthermore, Egypt's rapid population growth presents a pressing concern, as it is the most populous nation in the Middle East. The demand for electricity is projected to increase by 6.8% annually in the future [2]. Consequently, stakeholders in the construction industry prioritize the development of energy-efficient building designs. Over the past few decades, residential building investments in Egypt have surged, driven by both population growth and the concentration of a significant portion of the population in the Nile Delta region. According to United Nations data [3], Egypt's population reached more than 100 million at the mid-year point. To address this challenge, substantial expansions have been undertaken in the realm of building construction, with a predominant focus on quantity rather than the quality of living conditions. Unfortunately, this emphasis on quantity has led to substantial energy consumption that has not kept pace with the growth in electricity generation capacity in Egypt. Consequently, building energy consumption has escalated, primarily to meet the demands of cooling and lighting, as many of these structures were erected without due consideration for environmental sustainability and thermal comfort during their initial phases [4].

The residential sector, as depicted in Figure 1, accounts for approximately 52% of Egypt's total energy consumption [5]. Artificial lighting and electrical ventilation (air conditioning systems consume 56% of the energy used in buildings) represent major contributors to energy wastage.

Figure 1. Distribution of energy consumption for different sectors in Egypt [5].

Unfortunately, energy considerations in the design process are often insufficiently addressed by architects responsible for these buildings. Therefore, any effective measures aimed at reducing energy demands in this context would significantly contribute to mitigating the escalating costs associated with energy consumption. The achievement of well-being and the optimization of work effectiveness are contingent upon the provision of a favorable indoor environment. Among the facets of indoor environmental
quality, thermal comfort takes precedence over acoustic comfort, visual comfort, and indoor air quality [6]. To minimize the environmental footprint, there is need to harmonize thermal comfort with low primary energy consumption. Building owners and stakeholders generally seek to attain optimal thermal comfort conditions while minimizing economic costs [7]. A fundamental objective in building design is to create a comfortable environment for occupants while simultaneously curtailing the building's energy consumption. The building envelope, serving not only as a physical barrier between the exterior and interior environments but also as a dynamic regulator, assumes a pivotal role in responding to heating, cooling, ventilation, and natural lighting requirements [8]. The building envelope strike a delicate balance, accommodating the demands for ventilation and daylighting while furnishing adequate thermal insulation suited to local climatic conditions [9]. Building wall structures wield substantial influence in predicting energy consumption and greenhouse gas emissions [10]. Therefore, optimizing the design of the building envelope emerges as a critical element in achieving energy efficiency and human comfort [11]. Traditionally, in the context of Egypt's hot and arid climate, vernacular architecture favored external walls with substantial thickness as a passive strategy to attenuate heat transfer and delay the impact of harsh external conditions. However, this approach, although effective in enhancing the thermal performance of residential buildings, has fallen out of favor due to cost considerations and the need to conserve interior space within buildings [12]. Presently, half-red brick walls (12 cm thickness) are prevalent in the residential sector, primarily due to their comparatively lower initial cost compared to other wall specifications. Due to the population, increased electricity demand, plans for development, and the imperative to maintain comfortable living conditions, the incorporation of thermal insulation for building walls has emerged as a highly efficient means of reducing energy consumption for both cooling and heating purposes. Furthermore, the escalating cost of energy and the adverse environmental repercussions of energy production further underscore the urgency of devising solutions to significantly energy consumption [13]. Thermal insulation can be applied to external wall structures through three distinct methods: internal, external, and sandwich configurations. Figure 2 illustrates the structural layout of an external wall, comprising external plaster, insulating material, horizontal brick, and interior plaster. Conversely, Figure 3 illustrates the construction of a sandwich-type wall, consisting of horizontal brick, insulating material, internal plaster, and external plaster [13].

Figure 2. Structures of the external wall (modified after Auto-CAD).

Figure 3. Structures of the sandwiched wall (modified after Auto-CAD).

Thermal insulation materials refer to substances or combinations of substances that, when used appropriately, can reduce the transfer of heat. In the Egyptian construction market, various types of thermal insulation materials are employed for different parts of buildings. These types encompass blankets, concrete blocks, foam boards, insulating concrete forms, loose-fill and blow-in materials, rigid fibrous or fiber insulation, sprayed cementitious foam, and structural insulated panels. Each type is applied differently and offers distinct advantages depending on its specific application [14]. Two commonly used insulation materials in thermal insulation systems for building envelopes in Egypt are extruded polystyrene (XPS) and expanded polystyrene (EPS) [15]. For existing buildings located in hot climates, the Energy Research Center (EREC) recommends the utilization of XPS thermal insulation for building envelopes [16]. Prior studies in Egypt [2, 17-20], have highlighted the capacity of XPS insulation to enhance building thermal performance, and similar studies in different countries have also recommended the use of XPS due to its significant impact on energy savings and thermal comfort [21-24]. Moreover, the Egyptian market boasts a substantial manufacturing capacity for XPS insulation, known for its high durability and resistance to moisture transfer [17, 20]. XPS is characterized as an inorganic and rot-resistant insulation material. It possesses excellent attributes in terms of durability and its ability to resist moisture transfer, as indicated by the Housing and Building National Research Center [25]. Furthermore, XPS insulation boards are highly

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energy-efficient, lightweight, easy to handle, and offer stable long-term insulation properties.

II. LITERATURE REVIEW

Over the past decade, researchers worldwide have been actively developing guidelines for designing residential buildings with low energy usage, but their impact on construction practices in Egypt has been limited. Several studies have explored the integration of thermal insulation materials in external walls to optimize indoor thermal comfort and reduce energy consumption. Edeisy and Cecere [18] conducted a study in Egypt's hot arid climate, evaluating envelope retrofit options using two different types of insulation materials (EPS and XPS) at varying thickness levels. The results demonstrated that XPS significantly reduced cooling load and carbon emissions by 27.13%, while EPS achieved a 11.89% reduction in total building consumption, indicating that XPS was more effective at the same thickness.

Ameur et al. [26] found that modifying envelope elements had a significant impact on reducing energy consumption, albeit with a slight decrease in discomfort hours (less than 15%). This emphasized the importance of envelope elements in influencing indoor thermal conditions.

In Morocco, Boukhattem et al. [27] assessed various insulation materials available in the market, including cork, rock wool, glass wool, polyurethane, XPS, EPS, and perlite. They concluded that XPS offered superior energy savings compared to EPS and polyurethane insulation materials in several residential construction case studies.

Also, Laqir et al. [28] conducted a study in Morocco and reported that a 4 cm XPS roof insulation reduced the need for heating and cooling by 30% compared to a non-insulated building. This resulted in yearly energy consumption dropping to 42.61 kWh/m² per year, below the limit set by the Moroccan Thermal Construction Regulation (RTCM).

In Poland, Dylewski and Adamczyk [29] investigated the economic and environmental benefits of thermal insulation in buildings across different temperature zones. They found that using thermal insulation significantly reduced energy demands for HVAC equipment operation and reduced the overall environmental impact of buildings. The optimal insulation thickness varied with heating degree days.

In 2022, Kazanci and Samanci [30] designed a residential house and determined the optimal insulation thickness for external walls in different climate zones. They found that XPS was the ideal choice for the hot zone.

Given the promising results of these previous studies, it is evident that thermal insulation materials, especially organic polymer foam insulation boards like extruded polystyrene (XPS), offer an effective means of saving energy in buildings [31]. However, there remains a research gap in modeling thermal insulation materials for residential buildings using simulation software in the hot-arid climate of Egypt to achieve thermal comfort. Therefore, the primary objective of this study is to assess thermal comfort in residential buildings using the optimal insulation material based on previous research and its availability in the Egyptian market, utilizing Design Builder software. This study also aims to provide energy-saving solutions for middle-income citizens in medium housing projects. Additionally, the research considers Egypt's three climatic zones: semi-arid (Cairo), Mediterranean (Alexandria), and arid (Aswan).

III. STUDY AREA

A. Climate and location of Study area:

Egypt is geographically situated in the northern hemisphere, occupying a latitude range between 22° and 32°. Approximately one-fourth of its total land area is located south of the Tropic of Cancer, encompassing approximately 10 latitudinal degrees. Consequently, the entirety of Egypt's regions falls within the hot-dry climate zone, except for a narrow strip characterized by a Mediterranean climate. For the purposes of this study, the three primary climatic zones selected align with the categorization established by the Egyptian Residential Energy Code, which encompasses a total of eight climatic zones, as illustrated in Figure 4 [32].

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The three climatic zones were semi-arid (Cairo and Delta zone), Mediterranean (north coast zone), and arid (southern Egypt zone). The three main cities in those zones were Cairo, Alexandria, and Aswan respectively. Their average outdoor air temperature during the day in the middle of the summer ranged between 30°C in Alexandria to 41°C in the south in Aswan, while these maximum temperatures in the middle of the winter ranged between 18°C in the north and 23°C in the south [25]. A climate file with hourly data provided by ASHRAE for the Cairo, Alexandria, and Aswan regions used in the simulation, is illustrated in Table 1.

<table>
<thead>
<tr>
<th>City</th>
<th>Zone Type</th>
<th>Climate</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation above sea-level</th>
<th>CDD(^{(25^\circ \text{C})})</th>
<th>HDD(^{(18.3^\circ \text{C})})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cairo</td>
<td>Cairo and Delta</td>
<td>Semi-arid</td>
<td>30.13(^\circ)N</td>
<td>31.40(^\circ)E</td>
<td>74.00 m</td>
<td>296</td>
<td>344</td>
</tr>
<tr>
<td>Alexandria</td>
<td>Northern Coast</td>
<td>Mediterranean</td>
<td>31.20(^\circ)N</td>
<td>29.95(^\circ)E</td>
<td>7.00 m</td>
<td>153</td>
<td>469</td>
</tr>
<tr>
<td>Aswan</td>
<td>Southern zone</td>
<td>Arid</td>
<td>23.97(^\circ)N</td>
<td>32.78(^\circ)E</td>
<td>194.00 m</td>
<td>1278</td>
<td>127</td>
</tr>
</tbody>
</table>

B. Description of the case study:

Dar Misr project is considered one of the important projects of the Ministry of Housing, which is currently implemented in several governorates in Egypt with distinct sites and it is selected as a case study. The project consists of two building models (A-B) with varied sizes in apartments, the residential building area is 570 m² and consists of ground and five typical floors, consisting of four apartments per floor, the area of the case plan (130 m²) and a clear height of 3 meters at the typical floor of the model (A), as shown in Figure 5. It consists of a reception and dining space, three bedrooms, a kitchen, a bathroom, a toilet, and terraces.

IV. METHODOLOGY

A. Thickness of insulation layer:

The residential building energy standard for Egypt was released in 2009 by the HBRC, which is an organization connected to the Minister of Housing, Utilities, and Urban Communities (MHUC), the only national body in charge of issuing the Egyptian codes[25]. Code was the most common method used in studies to calculate the heating and cooling loads and the optimum insulation thickness.

Firstly, Because the thermal resistance and thermal conductivity for every material were variable in every climate zone to achieve thermal comfort, the total thermal resistance for all the consecutive layers was calculated in a structural element for external walls.

\[
R_t = \Sigma R_i
\]

\[
R_t = R_{ti} + R_1 + R_2 + \ldots + R_n + R_{si}
\]

Where: \(R_t\) is the total thermal resistance of the wall without the insulation, \(R_{ti}\) and \(R_{si}\) are respectively representing the inside and outside thermal resistances, \(R_1, R_2\ldots\) is the thermal resistance of each layer.

In the second step, according to EREC to determine the thermal resistance required in the climatic region of the case...
study (Cairo-Delta zone, Northern coast, southern Egypt zone), equation (3) was used.

\[ R^*_{e} = R_e + R_{in} \]  

(3)

Where: \( R_e \) is thermal resistance without insulation, \( R^*_{e} \) thermal resistance for climatic region zone, and \( R_{in} \) thermal resistance for insulation material.

The last step determines the thickness because thermal insulation resistance depends on both thermal conductivity (k) and thickness (L).

\[ R_{in} = \frac{L}{k} \]  

(4)

Where: \( L \) is the thickness of the insulation layer; \( k \) is the thermal conductivity of the insulation material.

B. External walls specifications:

The specifications for the wall constructions evaluated are presented in Table 2, in terms of layer component type, the thickness of each layer, and wall U-value. The base case, half red-brick wall, was one of the most used external walls in practice in Egypt since it has a relatively low initial construction cost. Figure 6 shows the layers of the insulation materials in Cairo, as well as the base case.

To calculate the improvement in thermal comfort after applying scenarios, the change in the number of thermal comfort hours was calculated during the base case and each scenario using the following equation 5:

\[ \Delta T_{TC} = \frac{T_{ref} - T_{new}}{T_{ref}} \times 96 \]  

(5)

Where:

\( \Delta T_{TC} \): Percentage of thermal comfort hours per year.
\( T_{ref} \): The total number of hours per year (8760 hr.)
\( T_{new} \): Not comfortable hours for base case and applied scenario.

The change in the energy consumption was evaluated for each scenario compared to the base case using the following equation 6:

\[ \Delta \%_{EC} = \frac{\sum C_{Sc} - C_{base}}{\sum C_{base}} \times 96 \]  

(6)

Where:

\( \Delta \%_{EC} \): % Change of energy consumption value.
\( C_{Sc} \): Energy consumption value in month for applied scenario.
\( C_{base} \): Energy consumption value in month for base case.

C. Thermal comfort measures:

There were six factors, environmental and personal parameters, that affect thermal comfort status. These factors may be independent of each other but together contribute to an employee's thermal comfort. The thermal comfort limits specified by EREC, which range from 21.8°C to 30°C when humidity levels are between 20% and 50% and the interior wind speed is between 0.5 and 1.5 m/s, were used to assess the comfort range analysis in this study[16]

<table>
<thead>
<tr>
<th>Case</th>
<th>Insulation type</th>
<th>External Walls</th>
<th>Thick. (cm)</th>
<th>U-Value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>without insulation</td>
<td>Half a wall of red bricks</td>
<td>12</td>
<td>2.158</td>
</tr>
<tr>
<td>Cairo</td>
<td>Scenario 1-1</td>
<td>Double wall of half-red brick with an extra 5cm of XPS thermal insulation layer.</td>
<td>29</td>
<td>0.468</td>
</tr>
<tr>
<td></td>
<td>Scenario 1-2</td>
<td>A full wall of red brick plus an additional 7cm of XPS thermal insulation layer.</td>
<td>26</td>
<td>0.336</td>
</tr>
<tr>
<td>Alexandria</td>
<td>Scenario 2-1</td>
<td>Extruded polystyrene (XPS)</td>
<td>Double wall of half-red brick with an extra 3cm of XPS thermal insulation layer.</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Scenario 2-2</td>
<td>Double wall of half-red brick with an extra 5cm of XPS thermal insulation layer.</td>
<td>20</td>
<td>0.466</td>
</tr>
<tr>
<td>Aswan</td>
<td>Scenario 3-1</td>
<td>Double wall of half-red brick with an extra 7cm of XPS thermal insulation layer.</td>
<td>31</td>
<td>0.367</td>
</tr>
<tr>
<td></td>
<td>Scenario 3-2</td>
<td>A full wall of red brick plus an additional 10cm of XPS thermal insulation layer.</td>
<td>35</td>
<td>0.277</td>
</tr>
</tbody>
</table>
D. Simulation tools:
The modeling process was conducted through dynamic thermal simulations, encompassing various wall specifications, climate zones, and weather data files. These simulations were executed using the 'Design Builder v6.5 software' due to its advantageous features such as extensive material libraries, flexible geometry input capabilities, and the inclusion of load profiles. Additionally, Design Builder was chosen for its incorporation of control methods that ensure the accuracy of research findings when compared to standalone Energy Plus engine simulations [34]. To construct the basic simulation model, the research team adhered to the prevailing construction details, materials, and systems within the areas under study. The primary objective of establishing this base model was to estimate the annual energy consumption for the case study project in its existing, non-retrofitted state. Subsequently, the role of each insulating material in altering the overall energy consumption was assessed by comparing it to the basic scenario.

E. Physical model characteristics:
The simulation is based on weather file data from Climate Consultant 6.0 every hour in the three main cities in Egypt: Alexandria, Cairo, and Aswan, input data are verified by the Egyptian building Code, considering the acquisition of solar energy, thermal conduction, and convection between zones of different temperatures. Summary of the main model input material and construction characteristics and the specifications of the A/C used in this building are summarized in Table 3:

V. RESULTS AND DISCUSSION

The results obtained from the simulation of the construction envelopes were divided into two separate graphs: Thermal comfort analysis (Hours) and Monthly Energy Consumption (kWh). These measures were plotted for the 3 climatic zones (Cairo, Alexandria, and Aswan).

A. Impact on thermal comfort analysis:
Thermal comfort was measured in terms of the number of hours of discomfort. The shortest discomfort period was the best scenario in which the suitable thickness was used in building construction to achieve optimal thermal comfort. The results of each scenario’s effect on thermal comfort were displayed first, and measurements of the walls' air temperature and surface temperature were presented for a year without using air conditioning units or fans.

Figure 8 shows that the simulation result of the base case study in Cairo in the comfort zone was about 2017 hours from 8760 thermal comfort hours over the year (23%). While the base case study in Alexandria in the comfort zone was about 1584 thermal comfort hours (18%), it reached 1820 thermal comfort hours (20.7%) in Aswan. It is deduced that the comfort hours in the Mediterranean climate have fewer reduction percentages compared to the arid climate and semi-arid climates.

In Cairo, the application of Scenario 1-1 had an impact on the thermal comfort inside the building at almost 31.7%, while in Scenario 1-2 the thermal comfort period reached 34.9%. Moving to Alexandria, there was a slight increase in thermal comfort through the simulation of Scenario 2-1 from 18% to 19.8%. This increase continued until reached 21.9% after the Scenario 2-2 simulation. A significant increase in the thermal comfort effect was observed in Aswan by 28.2% and 33.2% after the usage of Scenario 3-1 and Scenario 3-2, respectively. It is noticed that the greatest impact on thermal comfort appeared in Aswan by a difference of 12.4% compared to the base and 11.9% in Cairo. Although, the smallest impact was in Alexandria's case with 3.9% compared to the base this change cannot be neglected to provide more thermal comfort.
B. Impact on Energy consumption

This study focused on the annual energy consumption of an apartment for a separate single-family of 130 m². The energy consumption calculations include lighting, air conditioning, and equipment. The overall energy consumption was measured in kWh. The output from Design Builder was analyzed and compared mainly to the base case considering the annual energy consumption.

Figure 9 depicts fluctuations in monthly energy consumption for three different climatic zones (Cairo, Alexandria, and Aswan) for the base case and compared with other scenarios. As expected, energy consumption increased because the temperature increased under climate change in all the climatic zones.

In Cairo, there was a dramatic rise in the consumption of energy in the summer season (June, July, August, and September) due to increased solar radiation in these months until it reached 776.24 KWH in August, while the energy consumption gradually decreased during the winter period till it formed 318.77 KWH.

After applying both scenarios, it was found that there was a disparate drop in the monthly energy consumption during the year. The maximum value in energy consumption was in August, which reached 614.96 KWH using scenario 1-1 and 597.97 KWH using scenario 1-2. The total annual percentage reduction in energy consumption was around 12% and 14% in scenarios 1-1 and scenarios 1-2, respectively, as shown in figure 10. Therefore, the simulation showed that heating loads were not as critical as cooling loads in a hot arid climate like Cairo.
Figure 9. Monthly energy consumption for base case and different scenarios (Cairo, Alexandria, and Aswan respectively).
According to Alexandria, there was a significant increase in energy consumption in the summer season until it registered 644.77 KWH in August, while the energy consumption gradually declined during the winter period till it scored 304.14 KWH. For the applied scenario, it was found that there was an unequal reduction in monthly energy consumption during the year. The maximum energy consumption value was in August, which reached 564.97 KWH using scenario 2-1 and 510.4 KWH using scenario 2-2. The total annual percentage decrease in energy consumption was about 8% and 20% in scenarios 2-1 and scenarios 2-2, respectively.

The summer season witnessed a sharp rise in energy consumption in Aswan, reaching 978.25 KWH in July, while the winter witnessed a progressive fall in energy consumption, ending at 330.61 KWH. It was discovered that there was an uneven reduction in monthly energy use over the course of the year for the applicable scenario. The peak value for energy consumption was in July, reaching 749.46 KWH under scenario 3-1 and 684.61 KWH under scenario 3-2. The overall yearly percentage drop in energy consumption was roughly 13% and 22% under scenarios 3-1 and 3-2, respectively, as shown in figure 10.

The study's overall results indicated that the most commonly used construction method (half-wall of red bricks) had the highest energy consumption. Furthermore, when comparing all simulated scenarios to the reference case study, it became evident that the incorporation of insulation materials significantly improved the energy performance of the building and reduced the total energy required for operation.

VI. CONCLUSIONS

The primary focus of this study was to promote awareness regarding energy savings and indoor thermal comfort improvements achieved through enhanced building energy efficiency and the utilization of insulation materials. The research specifically examined a residential flat with an area of 130 square meters under various climatic conditions throughout the year. Optimal building envelope designs were conducted for the three predominant climate zones in Egypt: semi-arid, Mediterranean, and arid climates, represented by the cities of Cairo, Alexandria, and Aswan, respectively. The research explored numerous design alternatives for building envelopes in these three climate zones, with the goal of minimizing energy consumption and reducing thermal discomfort hours. The findings of this study are highly valuable for guiding the construction of future residential buildings in these regions. The results indicated that the optimal scenario, which involved a full wall of red brick plus an additional specified thickness of expanded polystyrene thermal insulation (XPS), significantly increased thermal comfort hours by up to 33.2% throughout the year, a crucial factor in hot climate regions like Egypt. Furthermore, this optimal scenario reduced energy consumption by at least 21.7% when compared to the second-best thermal performance wall specification, underscoring the substantial benefits of adopting such energy-efficient building practices.

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![Figure 10. Percentage reduction in energy consumption for scenarios.](image-url)
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