Analytic Modeling to Study the Insolation Heat Gain of Semi Insulated Building in Hot Climate

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***Abstract*— Countries located in temperate, hot and arid climates, such as Libya, face the critical need to cool houses whose internal temperatures rise due to these climatic conditions. This can be achieved by employing proper insulation techniques to prevent heat gain from solar radiation (insolation). This paper addresses the impact of not implementing thermal insulation for the roof of a building, in contrast to other external parts of the structure. The temperature distribution in a single-story building was studied using finite element analysis (FEA), along with how the building absorbs heat from its surroundings during a sunny day. The thermal analysis was conducted on a 3D concrete building with walls made of concrete masonry blocks, a floor height of 3.20 meters, and a total area of 40 square meters, using ANSYS 2020 R2 software. The building model includes thermal insulation for the external envelope, but the roof and openings remain uninsulated (as is often the case with home insulation practices in Libya). The finite element method is widely used due to its high effectiveness in simulation and achieving accurate results. The analysis results demonstrated the heat distribution gained from insolation, as well as variations in the rates of heat transfer from the building's exterior to its interior. The findings showed that neglecting the thermal insulation of the roof and window openings leads to an approximate 70% increase in the building's internal temperature. Furthermore, the results clearly indicated that insulating the building's walls alone is insufficient to prevent overheating. This provides a sufficient understanding of the prioritization required in applying insulation layers for buildings located in hot climates.**

Keywords— Ambient, Morphology, Insulation, Radiation, Sustainability, Insolation

I. INTRODUCTION

One of the most important factors in promoting environmental sustainability is improving buildings' energy efficiency. In the fields of construction, civil engineering, and architecture, many ideas have been introduced related to energy and natural resources, focusing on the shape of structures, the location and distribution of elements necessary to provide ventilation and capture solar radiation, such as windows, building aspect ratio, orientation of the block, position of vertical cores, and the structural system. Often, these variables directly depend on the climatic zone in which the building will be built [1].

Generally, in a hot and arid climate, such as that of Libya [2], the energy consumed for cooling is the highest in HVAC systems (Heating, Ventilating, and Air Conditioning). Therefore, the design of residential buildings must consider how to take advantage of the natural factors specific to the climate zone in which the house is located; the characteristics of building morphology can be manipulated to adapt to these features or to avoid their unwanted effects. The structural system and proper building configuration can contribute to reducing energy consumption for cooling and heating by up to 30%, depending on the climatic zone [3]. Furthermore, the implementation of thermal insulation layers plays a significant role in conditioning houses, but these layers must be applied successively, focusing on parts of the building that cause indoor temperature increases. Whether concrete, wooden, or steel buildings, as the air temperature differs between exterior and interior, heat transfers through walls, ceilings, floors, and openings. Part of this heat is stored in building components, while the rest penetrates into the rooms [4].

Thus, the heat transfer rate depends on the thermal resistance of the building's material components. Buildings gain heat primarily through convection—heat transferred through walls, ceilings, floors, and openings (windows and doors) due to the temperature difference between indoor and outdoor air. Secondly, radiation transfers heat through external walls, roofing, and openings exposed to sunlight. Thirdly, heat is generated from internal sources such as lighting, equipment, and occupants. Fourthly, heat transfer occurs via air leakage through cracks in openings [4].

In addition, thermal conduction plays a fundamental role in heat transfer through solid building components, particularly those with high thermal mass such as concrete walls and roofs. This mechanism involves the movement of thermal energy from regions of higher temperature to lower temperature at the molecular level, driven by temperature gradients. Concrete elements in the building envelope can store and gradually release absorbed heat, significantly influencing indoor thermal comfort and energy demand. The rate of heat conduction depends on the material's thermal conductivity, thickness, and surface area exposed to thermal differentials [5]. Understanding and accurately modeling thermal conduction is essential for optimizing insulation strategies and improving building energy efficiency, especially in regions with extreme climates. Recent studies show that polymer-modified concrete incorporating recycled polymers improves thermal damping and reduces heat transfer, offering more sustainable and energy-efficient building envelopes [6].

Moreover, glass openings significantly influence a building's thermal performance by allowing heat gain and

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loss, especially under varying outdoor conditions. Solar exposure through glazing can lead to overheating, while heat loss during colder periods increases energy demands. The use of high-performance glazing systems such as insulated glass units and low-emissivity coatings helps reduce these effects by limiting heat flow and controlling solar gain. Shading devices like louvers and blinds further mitigate radiation effects and improve comfort [7]. Ventilation also plays a key role; controlled ventilation enhances cooling and indoor air quality, while uncontrolled airflow may disrupt thermal balance. Systems such as double-skin façades and operable windows can optimize thermal efficiency when integrated with smart controls [8]. Overall, thoughtful design of glass openings and ventilation ensures better indoor comfort, energy efficiency, and environmental performance.

This study considers conduction explicitly in steady-state thermal analysis. Moreover, thermal radiation from internal masses such as walls and ceilings is considered implicitly, contributing to the overall heat balance.

Previous studies have shown that modifying the building envelope to match the local climate can reduce cooling energy consumption by approximately 31.4% [9]. Anderson et al. emphasized the importance of structural engineers working within integrated design teams to achieve sustainable structures [10]. The Structural Engineering Institute of ASCE published guidelines emphasizing material selection and life cycle cost analysis as foundations for structural sustainability [11]. Australia's Guide to Environmentally Sustainable Homes (Kestner, Taylor, & Henderson [12] and TecEco sustainable technologies [13] highlighted that while concrete has relatively low embodied energy, its extensive use in construction results in higher total embodied energy compared to other materials. Jones, Green, and Taylor developed methods for optimizing energy conservation balanced with solar energy, emphasizing cost-performance trade-offs in design decisions [14].

However, in Libya over the past decade, there has been increased promotion of thermal insulation materials and products by companies and factories. Citizens frequently inquire about suitable insulation materials and methods, especially after experiencing poor results in some cases where external thermal insulation layers were applied only to walls while neglecting roofs and openings.

Therefore, this paper studies heat gain rates from various external building elements—walls, roofs, and openings—to identify which parts require more thermal insulation. Considering Libya's summer climate, the analysis reveals how insolation heat distributes on structural surfaces and how heat transfer rates vary towards the interior. The results clearly show that insulating only the walls is insufficient to prevent indoor overheating. This provides a clear approach to implementing insulation layers in buildings located in temperate and arid climates like Libya's, enhancing sustainability and self-sufficiency.

II. Problem Statement

This study explores the effectiveness of thermal insulation on the building envelope and investigates how the absence of insulation on the roof and openings (windows and doors) may cause an increase in indoor temperature. It is important to note that, currently in Libya, thermal insulation is most commonly applied only to the external walls of buildings. The research employs the concept of thermal steady-state analysis, considering heat transfer mechanisms (conduction, convection, and radiation) through the main building elements: walls, roof, windows, and doors. This analysis examines how heat continuously transfers into the building from these surfaces under equilibrium conditions, contributing to indoor temperature rise. Other variables, such as occupant activity, number of residents, household appliances, and additional internal factors, are held constant to isolate the effect of building envelope components on thermal performance. The study aims to answer the key question: Why does indoor temperature remain high during summer even after insulating the building envelope except for the roof and openings?

III. Concepts and Methodology

The thermal energy that a room may absorb from both internal and external sources is commonly referred to as heat gain. This heat gain occurs primarily due to the temperature difference between the interior and exterior environments, which drives heat transfer into the building. Heat enters the indoor space through various pathways including air leakage, conduction through the building envelope's walls, ceilings, windows, doors, and ventilation systems. Among these, the building envelope plays a critical role in regulating heat flow and maintaining indoor thermal comfort. Heat transfer mechanisms involved include conduction (through solid surfaces), convection (due to air movement), and radiation (from solar exposure and internal surfaces). Accurately modeling these processes requires detailed analysis of material properties, surface areas, orientation, and environmental conditions, which can become highly complex. Given the scope of this study, the focus is narrowed to modeling heat gain exclusively from the building envelope components, neglecting internal heat gains and transient effects for simplification. This approach allows for a clearer understanding of how different elements of the envelope (walls, roofs, and openings) contribute to overall heat gain under steady-state conditions. By isolating these factors, the study aims to identify which parts of the envelope require prioritized thermal insulation to reduce cooling loads and improve energy efficiency.

A. Heat Transfer

Heat transfer is the flow of heat energy from a high-temperature body to a lower-temperature body, which is fundamental to the second law of thermodynamics. Calculating the resistance to heat transfer (R-value) of each material in the building assembly will yield the overall quantity of heat transported via the building's components. The three main methods of transferring heat are conduction, convection, and radiation (see Fig. 1). The definition of conduction is the transmission of heat energy from a source of higher temperature to a source of lower temperature through physical contact. Conductive heat transfer is described as occurring in stationary materials (solid bodies and immobile fluids). Convection is a mix of conduction and fluid movement that transfers heat whenever a surface comes into contact with a fluid that has a temperature that is different from its own. Electromagnetic waves that are emitted from a hot body and travel to a cold body are what cause heat transfer by radiation.

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Basically, this study shows that heat will transfer from the heated side of the material to the cooler side of the wall when one side is warmer than the other. The slope of the temperature gradient for a homogeneous wall is proportional to the thermal resistances (R-values) of the individual layers making up the composite wall, and the gradient is linear between the two surfaces. Resistance to heat flow, or R-value, is the reciprocal of thermal conductance, or U-value, which measures the rate at which heat flows through a material: R = 1/U. Substances with a strong resistance to heat flow can be used as insulation (high R-value and low U-value) [15].

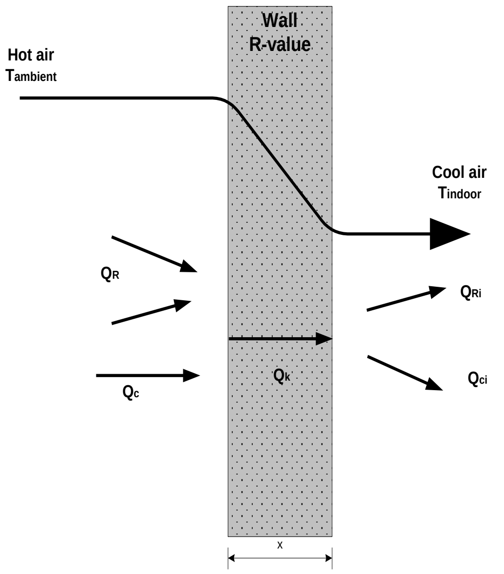

Fig.1: Heat exchange configurations

Nevertheless, this work is focused on heat gained by convection and radiation as boundary conditions, while conduction heat transfer depends on the properties of the materials used for the model envelope. The basic equations are as follows [12, 16].

$$Q_k = k\,A\,\partial T/\partial x \quad (1)$$

$$Q_C = h\,A(\Delta T) \quad (2)$$

$$Q_R = A\,\varepsilon\,\sigma\,(T^4 surface - T^4 ambient) \quad (3)$$

Where:

Q_k: the rate of heat flux by conduction (Watts)

k: the thermal conductivity (W/m k)

$\partial T/\partial x$: change of temperature with respect to x which is wall thickness (k/m)

Q_C: heat flux by convection (watt)

A: the surface area (m^2)

h: heat transfer coefficient difference (w/m2 ºC)

ΔT: difference in the surface temperature T surface & ambient temperature T ambient

Q_R: heat flux by radiation (watt)

σ: Stefan-Boltzmann constant (5.6696E-8 W/m^2.^{0}k^4)

ε: Emissivity unit less

B. Building and Material

The building is a typical sized room in the geometry of a warm climate zone. The plan view and cross section are shown in Fig. 2. The walls of the building (thermally insulated walls) consist of concrete masonry with a thickness of 20 cm, the uninsulated roof consists of reinforced concrete of 15 cm in thickness, the uninsulated windows are made up of single-layer standard glass, and the uninsulated door is made up of oak wood. In Table 1, the thermal properties of the material are presented. Fig. 3 shows the temperature of July 21 [17], which is a typical summer design day for calculating cooling and heating load for a temperate climate zone, such as Libya state. It represents a hot climate condition and is used here as a typical summer day design scenario for heat load estimation in arid zones such as Libya state.

TABLE 1: THERMAL PROPERTIES OF THE MATERIAL

Material type	Density Kg/m^3	Thermal conductivity w/m ºC	Specific Heat J/kg ºC	*Convection coefficient w/m^2 ºC
Concrete slabs	2400	0.75	666	2.37
Concrete masonry	2000	0.7	836	2.74
Glass	2300	1.05	836	3.83
Wood oak	825	0.21	2385	1.55

*Convection coefficient for Interface between solid surface and air

IV. MODELING

Using ANSYS 2020 R2 [18, 19], to run thermal finite element analysis, this FEA considers the thermal behaviors of both types of material: structural and non-structural, in the room's envelope. Moreover, the room is modeled in three dimensions as a scale model. Since the model consists of materials that differ in thermal properties, the element type is selected to be a solid element because all the components of this structure are solid except the inside air. It means there are fewer assumptions, which leads to more accuracy.

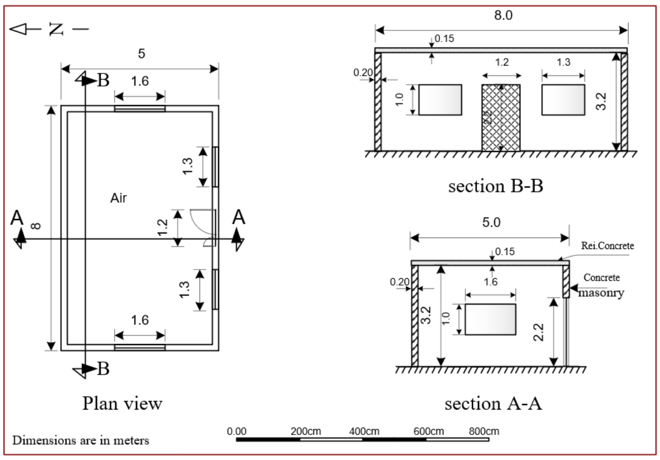

Fig 2: Room floor plan view & cross sections

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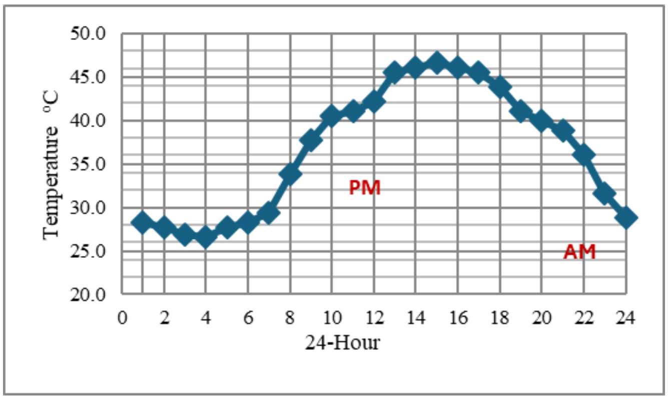

Fig. 3: Typical summer day design temperature of July 21

A. Steady-State Analysis

At an initial room temperature of 20 °C. the steady-state thermal analysis is provided to study the static heat transfer between different building components due to the change in the surrounding temperature, which corresponds to the daylight hours. In other words, in the analysis settings, the number of steps is 24 steps. Each step has a different magnitude of the temperature, so here it does not matter the duration of loading. Time is used for steady state multi-step and transient analysis. Since the walls are thermally insulated, radiation boundary conditions are applied to all the openings and the roof, while the convection boundary is applied to all interior surfaces. Meshing size is controlled by a convergence study of maximum temperature as shown in Fig. 4.

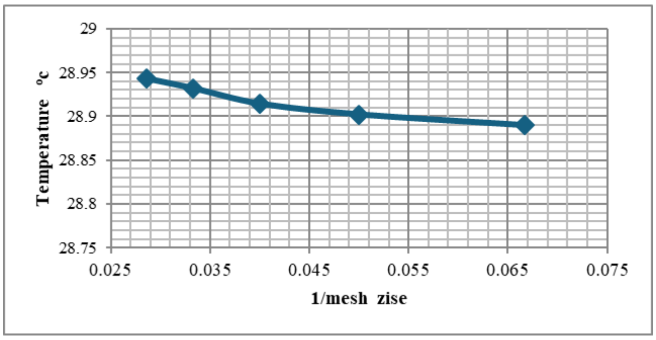

Fig. 4. convergence study of maximum temperature

B. Results

The results of the FEM analysis showed the behavior of the temperature distribution in the different parts of the room, where the highest temperatures are observed in the roof (45°C) and windows (40°C), and this behavior is expected because the roof and the openings are not thermally insulated, but also note that the walls gain heat even though they are thermally insulated (average of 31 °C) See Fig. 5. As the heat resulting from room insolation was transferred through the ceiling and the openings at different rates according to the thermal conductivity characteristic of each material.

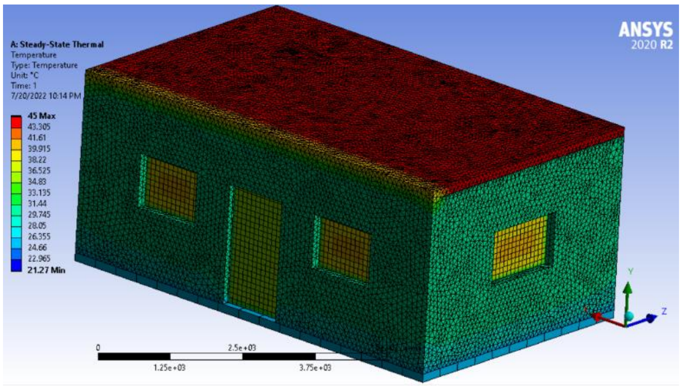

Fig. 5. Temperature distribution on the room envelop.

Also, this heat will be distributed through the air molecules inside the room due to the characteristic of convection heat transfer (see Fig. 6). This leads to a gradual rise in the room temperature during the day, as the room temperature increased from 20 °C to 45 °C near the ceiling and also led to the walls gaining heat from 20 °C to 31 °C, as well as 40 at the openings. This causes the room temperature to rise by 70%. Fig. 7 shows the total heat flux emitted by unit area from the parts of the building that are not thermally insulated; and since the walls are thermally insulated for the external fabric, they act as a retainer for the heat gained from the roof and windows through their inner surface and through their mass connected to heat sources.

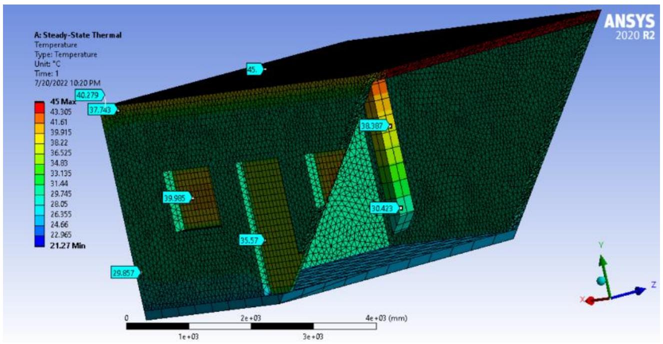

Fig. 6: Temperature distribution on envelops and inside the room

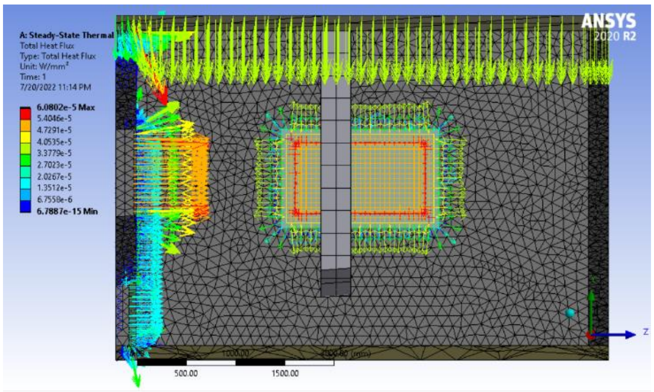

Fig.7: heat flux from elements that are not thermally insulated

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V. Conclusions

In the context of improving the construction system of the building to improve energy efficiency, this research considered the method of reducing the energy consumption needed to cool residential buildings, as it is most often insulating the building envelope without insulating the roof and the openings. This technique of thermal insulation of buildings is a commercial process, somehow not subject to a precise scientific methodology that considers the local climatic conditions and the materials used in addition to the method of implementation. Neglecting the thermal insulation of the roof of the building and the openings leads to a rise in the building temperature by approximately 70%. The results of the thermal study demonstrate that it would not get the desired result from insulating only the building envelope and neglecting the roof and the openings. Moreover, in the presence of the external insulation layer, and due to the thermal mass property of building materials, will cause the building's temperature to rise even at night. Therefore, to avoid a high temperature inside the building because of the high summer temperature, this study recommends that thermal insulation work be done for the entire building envelope (walls and roof), also recommends the use of glass for windows which has higher thermal insulation properties. Correspondingly, this study recommends focusing on the proper selection of insulation method and materials (it is known that the best insulator is the dead air). Finally, this study recommends that even in the case of a multi-story building, the thermal insulation of the upper floor surface must be implemented because due to the thermal mass characteristic of the building materials, the temperature accumulates in the elements and over time affects the lower floors gradually.

VI. Recommendations

Based on FEM tools, future research should analyze a broader range of building types and configurations commonly found in hot climates. This includes multi-structure developments, multi-zone buildings, and buildings with varying thermal mass, insulation systems, and façade materials, as well as differing in size, function, and architectural design. Incorporating such diversity will enhance the generalizability and practical relevance of the findings. Moreover, subsequent studies should conduct a detailed thermal analysis of various types of glass openings (e.g., single, double, and low-E glazing). This should involve the application and clear explanation of relevant heat transfer comparisons, including those governing solar heat gain and thermal transmittance. Additionally, future studies should integrate both natural and mechanical ventilation strategies into thermal simulations to better capture their influence on indoor thermal performance and energy efficiency.

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