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Research Article

THE EFFECT OF DIFFERENT INSULATION MATERIAL ON THERMAL COMFORT IN A BUILDING WITH NOZZLES COOLING SYSTEM

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Abstract: *A global analysis of energy consumption reveals a downward trend in capacity, while energy demand continues to increase in response to population growth. In this context, the significance of efficient energy utilization, particularly the reduction of heat losses in buildings, has grown considerably. Insulating buildings is a strategy that has the potential to minimize heat loss during winter months and overheating during summer months. This, in turn, can reduce the energy needed for heating and cooling systems, including air conditioners. The present study investigates the impact of insulation on thermal performance using a small, single-story wooden building model. The experimental design involved the insulation of the model's exterior walls with three distinct types of materials during the summer months. The experimenters recorded indoor and outdoor temperatures and calculated total heat loss (or gain) to assess the effects of insulation material on thermal comfort. The experiments were repeated with different building orientations, while radiation intensity and wind speed were also measured for a comprehensive analysis.*

Keywords: *Energy, Insulation, Thermal Performance, Heat Transfer*

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1. Introduction

Energy is among the fundamental necessities of modern societies, playing a critical role in economic growth and societal well-being. Factors such as population growth, industrialization, and urbanization have collectively led to a substantial increase in energy demand, thereby exerting significant pressure on available resources [1]. The judicious utilization of energy resources is imperative not only to curtail expenditures but also to mitigate environmental degradation. Among the various strategies employed to address this issue, energy efficiency has emerged as a potent instrument for achieving the delicate balance between economic growth and sustainability objectives [2]. In this regard, thermal insulation in buildings emerges as a pivotal application for energy conservation, reduction of heat loss, and enhancement of thermal comfort for occupants [3].

Over the years, extensive research has been conducted to evaluate the influence of insulation material types and thicknesses on energy efficiency and thermal performance. For example, Arif [4] investigated the energy savings potential of various insulation thicknesses in the Elazığ region, identifying optimal configurations for reducing energy consumption. Similarly, Semiha and Emre [5] applied a life-cycle cost analysis approach, concluding that expanded polystyrene (EPS) combined with coal offered the most cost-effective insulation solution. Erdem and Volkan [6] extended the analysis to three different cities in Turkey, determining optimal insulation thicknesses based on regional climatic conditions and economic considerations. Hüseyin et al. [7] focused on the Yalova region and found that a minimum insulation thickness of 2 cm is required to achieve satisfactory energy efficiency. Further studies have explored the long-term benefits of insulation materials, such as energy savings and reduced payback periods, across various regions and climates [8]-[13].

These investigations have demonstrated that selecting the appropriate insulation material can significantly influence a building's operational energy efficiency, particularly in regions with extreme climatic conditions. Advanced insulation materials, such as aerogels and phase-change materials (PCMs), have shown superior performance in regulating heat flow compared to conventional insulation options. Their ability to adapt to temperature fluctuations enhances indoor thermal stability while reducing energy consumption for heating and cooling purposes.

Beyond energy efficiency, sustainable insulation solutions contribute to environmental conservation by lowering greenhouse gas emissions associated with excessive energy use. Erzen et al. [14] emphasized the importance of integrating bio-based insulation materials, such as hemp and cellulose fibers, as viable alternatives to synthetic insulations. These materials not only provide effective thermal resistance but also support circular economy principles by utilizing renewable and biodegradable resources. Additionally, insulation materials with high resistance to moisture and microbial growth, such as extruded polystyrene (XPS), have been recognized for their long-term durability and reduced maintenance costs.

In addition to material selection, optimizing insulation thickness is a crucial factor in maximizing energy efficiency. Various studies have employed computational modeling and life-cycle cost analyses to determine the ideal insulation thickness required for different climatic zones, ensuring that energy savings offset initial investment costs. Recent advancements in smart insulation technologies, such as thermally adaptive coatings and dynamic insulation systems, have further expanded possibilities for improving thermal performance by responding dynamically to environmental conditions.

These findings highlight the necessity of a holistic approach to insulation design that incorporates material properties, optimal thickness, climate adaptability, and economic feasibility. Future research should focus on hybrid insulation systems that combine multiple materials to achieve enhanced thermal resistance and energy conservation. Additionally, integrating insulation solutions with renewable energy technologies, such as photovoltaic panels and geothermal heating, presents a promising avenue for advancing net-zero energy buildings. By leveraging these innovations, the construction industry can move toward a more sustainable, energy-efficient future, reducing both operational costs and environmental impact.

2. Material and Methods

To analyze the thermal performance under various experimental conditions, a one-story, one-room, one-roof building model was constructed using medium-density fibreboard (MDF) material. Thermocouples were installed on a side wall of the building, on the roof, and on the floor at strategic locations to provide accurate temperature measurements. In addition, a nozzle bundle of 25 nozzles was integrated into another wall of the building. Indoor temperatures were monitored using these thermocouples, air was introduced into the room through the nozzle bundles, and hot air was exhausted using an aspirator to provide effective air circulation throughout the building. The experiments were carried out on the terrace of the Mechanical Engineering Department of the Faculty of Engineering of Fırat University.Schematic illustration of experimental setup given in Fig.1.

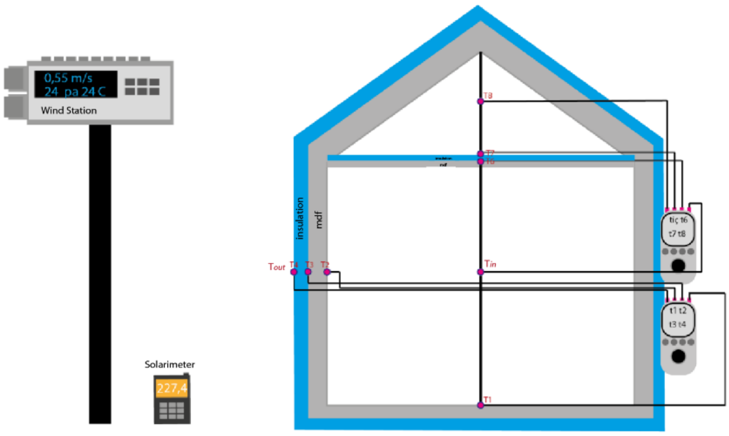
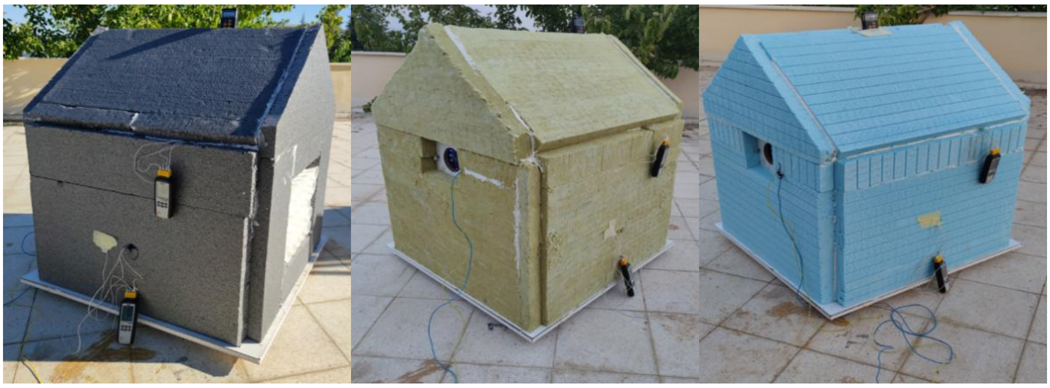


Fig.1 Schematic View of Experimental Setup

The exterior surfaces of the building and the roof cavity were covered with different types of thermal insulation materials (**Figs.1-2**). The experimental design includes a total of 36 tests covering all aspects of the building. Temperature measurements were taken simultaneously with two four-channel thermometers and recorded digitally. Instantaneous solar radiation was measured automatically with a radiation meter, while outside temperature, wind speed and direction were measured with a wind station.



a) b) c)

Fig.2 Picture of a building covered with a) EPS b) Stone-wool c) XPS thermal insulation material

The measurements were obtained during two distinct time periods: from 8:00 a.m. to 4:00 p.m. (daytime) and from 9:00 p.m. to 5:00 a.m. (nighttime). The collected data were then meticulously arranged into graphs to facilitate analysis and visualization. The effect of radiation was significant during the daytime hours and was taken into account in the calculations, while at night the effect of radiation was either completely negligible or absent. This comprehensive experimental setup aims to analyze in detail the effects of insulation materials on energy savings and thermal comfort.

2.1. Calculations

The following equations were used to make the necessary calculations in the experiment. Heat loss from side walls and roof:

$$q_{rad} + \frac{T_{out} - T_4}{\frac{1}{h_{out}}} = \frac{T_4 - T_3}{\frac{l_i}{k_{iy}}} = \frac{T_3 - T_2}{\frac{l_l}{k_l}} = \frac{T_2 - T_{in}}{\frac{1}{h_{in}}} \tag{1}$$

$$F = 0.5\, Re^{2/3} \tag{6}$$

$$q_{side} = q_{rad} + \frac{T_{out} - T_4}{\frac{1}{h_{out}}} \tag{2}$$

$$q_{fl} = \frac{T_1 - T_{\mathrm{in}}}{\frac{1}{h_{\mathrm{in}}}} \tag{3}$$

$$q_{rf} = \frac{T_7 - T_6}{\frac{l_s}{k_s}} \tag{4}$$

Nusselt calculation for circle nozzle [15]:

$$\frac{Nu}{P_r} = K \times G \times F \tag{5}$$

$$K = [1 + (\frac{H/D}{0.6/A_r^{1/2}})^6]^{-0.05} \tag{7}$$

$$G = 2Ar^{1/2} \frac{1 - 2.2Ar^{1/2}}{1 + 0.2\left(\frac{H}{D-6}\right) Ar^{1/2}} \tag{8}$$

Heat loss from nozzle Wall:

$$Nu = \frac{h\, d}{k} \tag{9}$$

$$q_n = h\,(T_{out} - T_{\mathrm{in}}) \tag{10}$$

$$q_{nw} = \frac{q_{side}\, A_f + q_n \sum A_n}{A} \tag{11}$$

Calculation of the radiation intensity falling on the side surfaces

The heat flux values measured by the solar meter for the horizontal plane were calculated for the vertical plane. The geometric factor R_b is defined as the ratio of the instantaneous direct radiation (I_b) falling on the inclined surface to the instantaneous direct radiation (I_b) falling on the horizontal surface, for the northern hemisphere this value is found from the following expression [16].

$$R_b = \frac{\cos(\varphi - \beta) \times \cos\delta \times \cos\omega + \sin(\varphi - \beta) \times \sin\delta}{\cos\varphi \times \cos\delta \times \cos\omega + \sin\varphi \times \sin\delta} \tag{12}$$

Here:

φ = Latitude angle
β = Inclination angle of the surface in horizontal position
ω = Clock angle
δ = Declination angle

Latitude angle =38.7° for Elazığ province.

The hour angle converts local solar time (LST) into the number of degrees the sun moves across the sky. Since the Earth rotates 15° per hour, each hour of solar noon corresponds to 15° of angular movement of the sun across the sky and is calculated by the formula.

$$\omega=15°\times(LST-12) \tag{13}$$

3. Results And Discussions

The side wall where the thermocouples were placed (Fig. 1) was oriented north-south-east-west, and the effect of orientation was taken into account in the heat transfer calculations. Graphs were plotted at one-hour intervals between 08:00 and 16:00 for daytime hours and between 21:00 and 05:00 for nighttime hours. Since the effect of radiation is high during daytime hours, it is taken into account in the calculations. In addition, the instantaneous wind speed was measured during the experimental hours and recorded in a table.

Figs. 3a-d show the heat flux vs. time graphs during the daytime hours for the side-wall-ceiling-floor-nozzle wall covered with EPS 4 cm insulation material. Fig. 4 shows the radiation intensity-time graph. Then the instantaneous wind speed table is given. Fig. 5 and Table. 2 show the results for the night time.

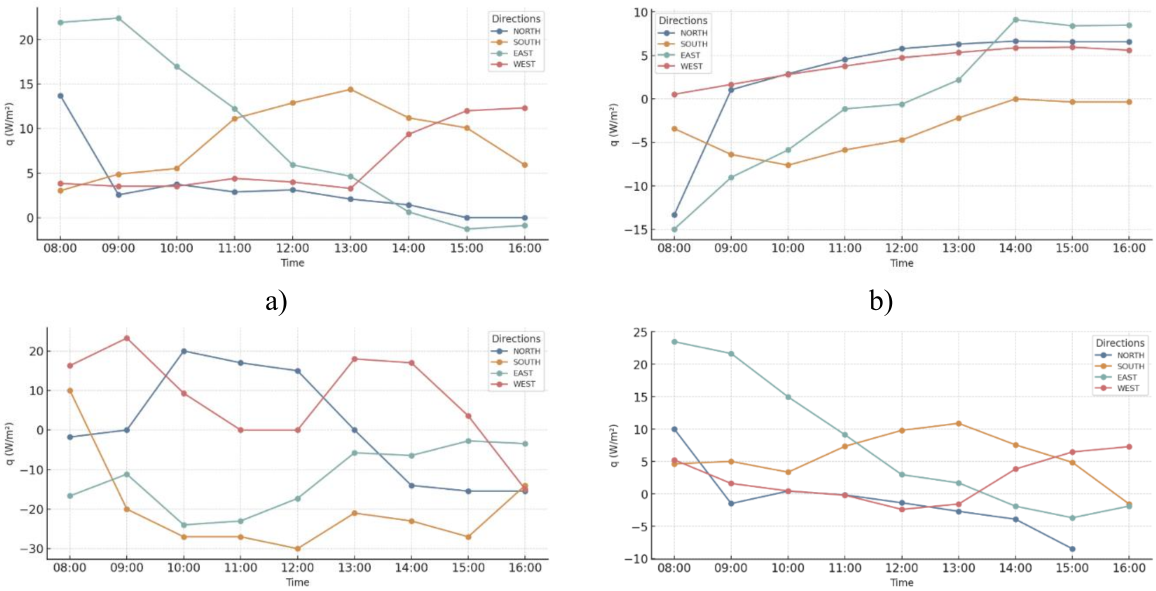


Fig. 3 Variation of heat flux with time for EPS 4 cm a) daytime-side Wall b) daytime - ceiling c) daytime-floor d) day-nozzle

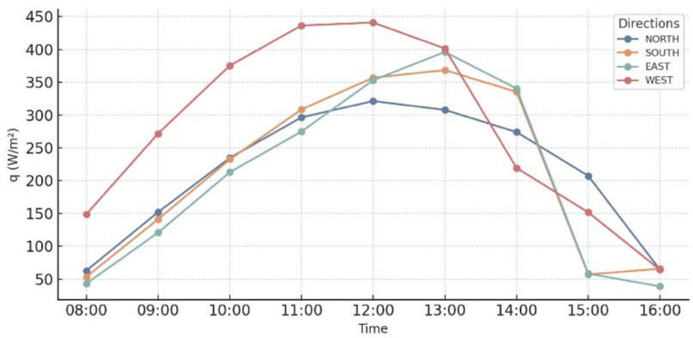


Fig. 4 Variation of the radiation intensity incident on the vertical surface with respect to time for EPS 4 cm

Table 1. EPS 4 cm instantaneous daytime wind speed values (*m/s*)

Time	North	South	East	West
08.00	0,7	0	0	0,7
09.00	0,7	0,7	0,7	1
10.00	1	1	1,7	2
11.00	0,7	2,7	2,7	2
12.00	3,7	2,7	2	2,7
13.00	2,7	5,1	3,1	1
14.00	1	4,8	1,7	3,7
15.00	2	2,7	1,7	4,8
16.00	2	3,7	2	3,1

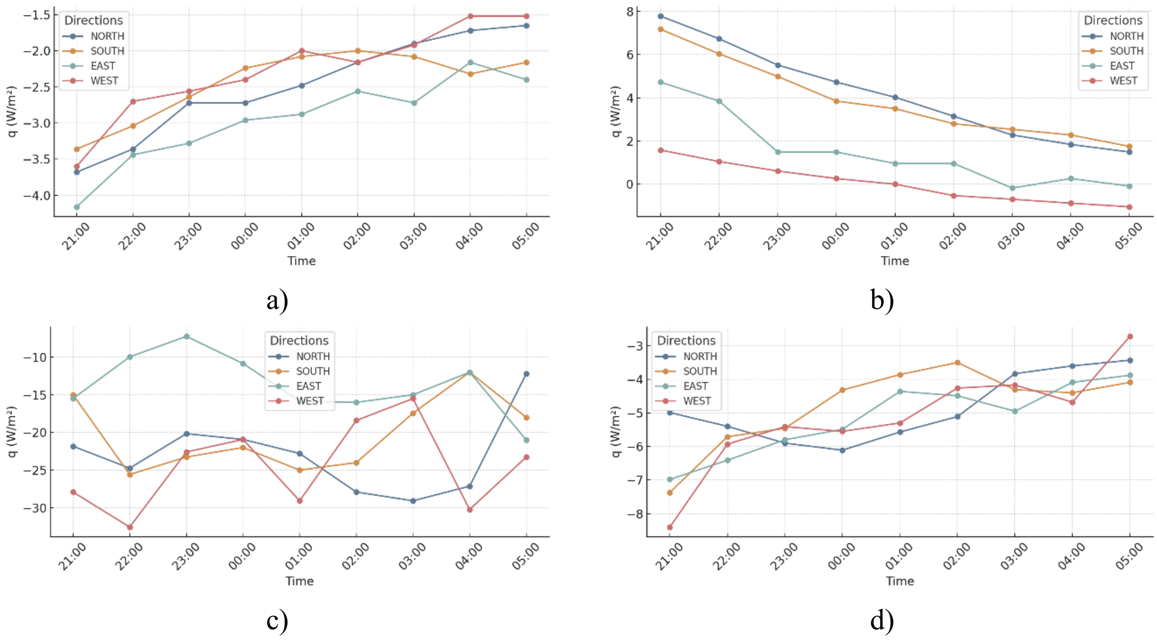


Fig. 5 Variation of heat flux with time for EPS 4 cm **a)** night-side wall **b)** night-ceiling **c)** night-flooring **d)** night-nozzle

Table 2. EPS 4 cm instantaneous wind speed values at night (*m/sec*)

Time	North	South	East	West
21.00	2	0	0,7	0
22.00	0	0,7	0,7	0,7
23.00	0,7	0,7	0,7	0
00.00	0,7	0	0,7	0
01.00	0	0	0	0
02.00	0,7	0,7	0	0
03.00	0,7	0	0,7	0
04.00	0	0	0	0,7
05.00	0,7	0,7	0,7	0,7

Fig. 3a. shows the heat transfer (q) through the side wall during daytime hours for EPS 4 cm. On the east-facing wall, q is higher in the morning and decreases later in the day, while on the west-facing surface, on the contrary, it is lower in the morning and increases in the afternoon. On the south-facing surface, q increases until noon and then decreases. On the north-facing surface, q is larger in the morning and decreases later in the day. This trend is similar for other insulation materials.

Fig. 4a. shows the heat transfer through the side wall at night for EPS 4 cm. As can be seen from the figure, the east and north facing surfaces cool down faster at night while the south and west facing surfaces cool down later.

When the heat transfer through the ceiling for EPS 4 cm during daytime hours is analyzed (Fig. 3b), it is seen that q increases from the morning hours in all directions of the building and reaches maximum values between 14-16 hours.

Fig. 4b shows the heat transfer through the ceiling at night for EPS 4 cm. Contrary to the daytime hours, q decreases gradually until the morning and reaches minimum values between 05-08 hours.

As illustrated in Fig. 3c, the heat transfer through the floor during daytime hours for EPS with a thickness of 4 cm is depicted. In all directions, q shows an approximately horizontal trend. However, in the experiments conducted on the south side of the building, this trend was temporarily disrupted due to the sudden appearance of a wind after 11:00 a.m. (see Table 2). This was followed by the closure of the air and the decrease in radiation intensity (a similar situation occurred on the north side after 12:00 p.m.). The horizontal trend in q, with the exception of sudden changes in conditions, is consistent for all insulation thicknesses and types, extending even during nocturnal periods (Fig. 5c).

Fig. 3d shows the heat transfer through the nozzled wall during daytime hours. As can be seen from the figure, the nozzled system was not very effective during daytime hours. It is seen that the nozzled system is effective after 17-20 hours and rapidly decreases the indoor temperature (Fig. 5c). This effect continues until 07-08 am the next day. After 08:00 am, the indoor environment starts to warm up again and the temperature increases rapidly.

The maximum indoor temperatures of the day are recorded between 15:00 and 16:00. In order to forestall the precipitous rise in indoor temperature during daylight hours, it is advisable to maintain the closure of windows (and, by extension, the nozzles) from 8:00 a.m. onward until the evening hours.

Fig. 4 shows the variation of radiation intensity with respect to time for EPS 4 cm. Table 3.1 shows the instantaneous wind speed during the daytime hours on the days when the EPS 4 cm experiments were conducted. Table. 2 shows the wind speeds at night on the same days.

As illustrated in Figure 6a, a comparison was conducted of 4 cm-thick insulation materials during daytime hours with the side wall facing east. As depicted in the figure, the lowest q is obtained in XPS during the early morning hours. At noon, there is no significant difference in q between the insulation materials.

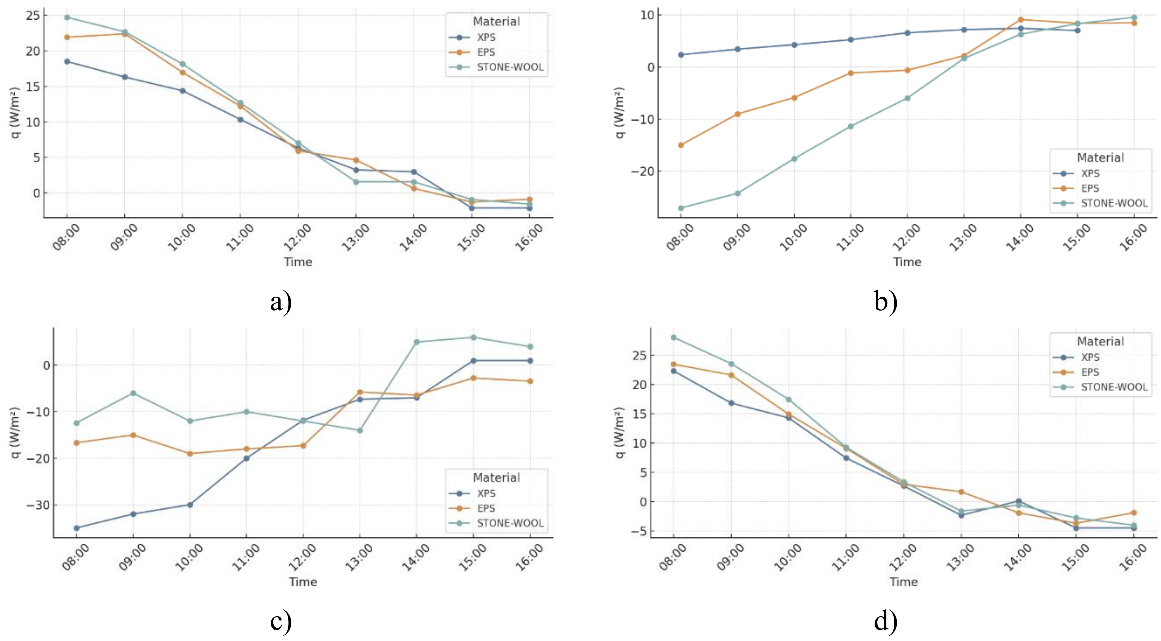


Fig. 6 Comparison of 4 cm thick insulation materials a) daytime-side wall b) day-ceiling c) daytime-flooring d) day-nozzle

Fig. 6b shows the values found for the ceiling at the same thickness during daytime hours. In this figure, in contrast to the previous one, XPS was the highest in the morning hours. However, the results are significantly affected by the fact that both the radiation intensity decreases and the wind speed is much higher on the test days with other insulation materials (Fig. 4, Table 1). Figs. 6c-d show the heat transfer from the floor and nozzled wall respectively under the same conditions. In both figures, it is seen that the lowest values of q are obtained for XPS in the morning hours. Figs 7a-d graphs plotted at night time.

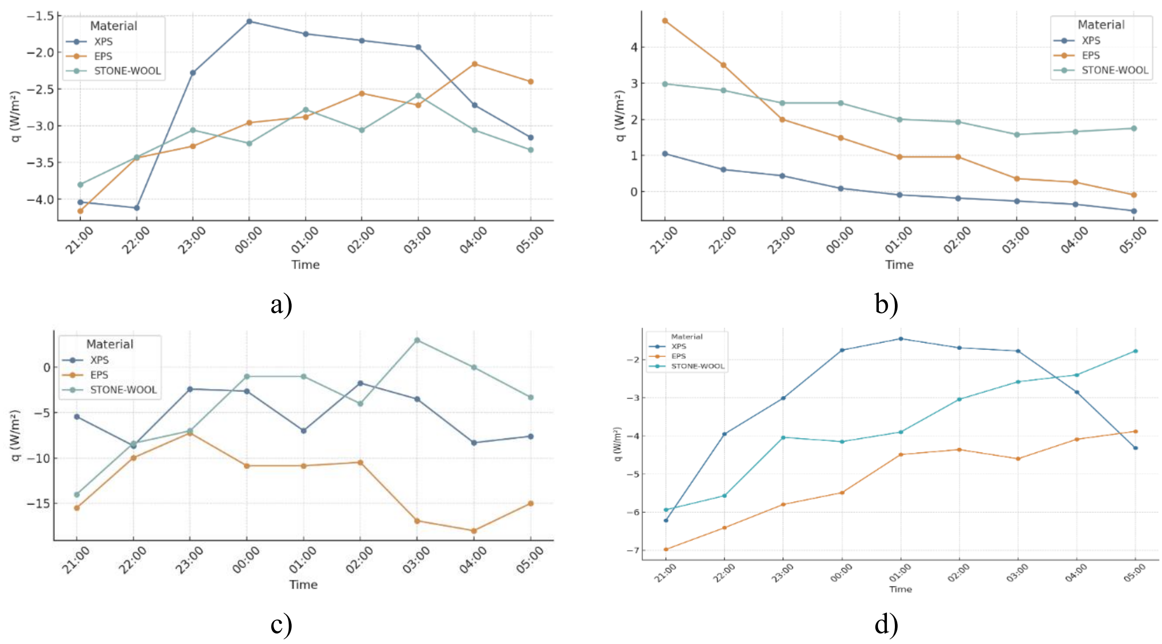
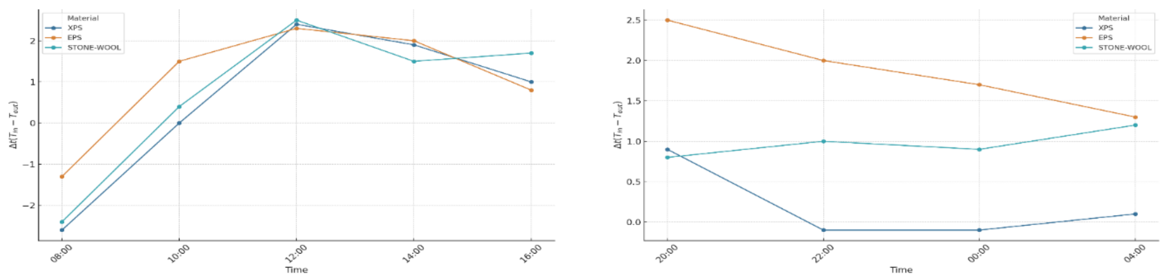


Fig. 7 Comparison of 4 cm thick insulation materials a) night-side wall b) night-ceiling c) night-flooring d) night-nozzle

The figures presented above illustrate the heat transfer from each wall of the building individually. However, due to the variability in weather conditions on the test days and at the time of the experiment, it was not feasible to calculate the total heat transfer from the building on the same day. The following figures are given to compare the inside-outside temperature differences for the north-facing nozzle (exterior wall direction east). Figs. 8a-b show the variation of 4 cm thick insulation materials with respect to each other during daytime and nighttime, respectively.



a) b)

Fig. 8 Comparison of temperature differences for insulation materials with 4 cm insulation thickness a) daytime - north facing nozzle direction b) night - north facing nozzle direction

As illustrated in **Fig. 8a-b,** the XPS-nozzle system demonstrates optimal cooling during the early morning and nighttime hours.

3.1. Uncertainty Analysis

In this study, the uncertainties in the measured values are evaluated using the Kline and McClintock [17] methodology. This method offers a structured and reliable approach for quantifying measurement uncertainties, ensuring the accuracy and credibility of the experimental results.
With uncertainty analysis, the error rate is obtained by *Eq.14* .

$$W_R = [(\frac{\partial R}{\partial X_1} W_1)2 + (\frac{\partial R}{\partial X_2} W_2)2 + (\frac{\partial R}{\partial X_3} W_3)2 + ... + (\frac{\partial R}{\partial X_n} W_n)2] \quad (14)$$

In a measurement with *n* independent variables.

R: dimension to be measured

$X_1, X_2, X_3, ..., X_n$: are the variables affecting the measurement

$W_1, W_2, W_3, ..., W_n$: is the error rate due to the independent variable

W_R, is the total uncertainty ratio.

In the experimental study, measurements were obtained by means of digital thermometers. In the experimental setup, the results were affected by errors due to thermometer and temperature measurement. Akpınar [18] stated some of the error amounts in his article as follows. According to these values, the error rate resulting from the study was calculated as shown below.

a. Error due to digital thermometers = ±0.1 °C
b. Error due to thermocouples = ±0.25-0.5 °C
c. Error due to points and fasteners = ±0.1 °C
d. Error in measuring the center temperature = ±0.25°C
e. The average error that can be made in measuring ambient temperature = ±0.25°C

$$W_R = [(a)^2 + (b)^2 + (c)^2 + (d)^2 + (e)^2]^{½} = [(1)^2 + (0.5)^2 + (0.1)^2 + (0.25)^2 + (0.25)^2]^{½} = \pm 1.176°C$$

4. Conclusions

The present study evaluated the thermal performance and energy efficiency of three distinct insulation materials—expanded polystyrene (EPS), extruded polystyrene (XPS), and stone wool—in a single-story wooden building model. The findings yielded significant insights into the effectiveness of these materials in enhancing indoor thermal comfort and reducing energy consumption. The findings demonstrated distinct advantages for each material depending on the building orientation and environmental conditions.

Table 3. Comparison of the lowest indoor temperatures of all insulation materials during night hours

T_{in}	West	East	South	North
Eps	**25,2**	25,3	25,5	**22,3**
Xps	24,5	27,6	25,2	25,8
Stone-Wool	25,3	**21,9**	**23,1**	25,5

XPS insulation consistently outperformed other materials in reducing heat transfer during both daytime and nighttime. It achieved the lowest recorded indoor temperature in the west orientation (24.5°C) and performed efficiently across other directions, showcasing its effectiveness as a thermal barrier, especially in regions with significant diurnal temperature variations. Stone wool excelled in specific orientations, achieving the lowest overall indoor temperature in the east direction (21.9°C) and demonstrating its suitability for targeted applications. EPS insulation, while slightly less effective overall, achieved the lowest temperatures in the north (22.3°C) and west (25.2°C) directions, indicating its potential for these orientations.

The integration of a nozzle cooling system has demonstrated effectiveness in reducing indoor temperatures during nighttime, thereby enhancing thermal comfort. However, its limited influence during the daytime suggests the need for optimization. Potential improvements include coupling the system with advanced ventilation controls, automated shading mechanisms, or complementary passive and active cooling strategies. Furthermore, external environmental variables such as solar radiation intensity, wind speed, and ambient temperature fluctuations play a crucial role in heat transfer dynamics. These factors must be carefully considered when designing and assessing insulation performance to ensure optimal energy efficiency and indoor climate stability.

These findings highlight the necessity of selecting insulation materials based on a combination of building orientation, local climatic conditions, and operational requirements. For instance, extruded polystyrene (XPS) is particularly suitable for regions that demand a robust thermal barrier across various orientations due to its low thermal conductivity and moisture resistance. Conversely, stone wool may offer superior performance for eastern and southern-facing walls, where solar exposure patterns necessitate materials with high thermal mass and fire resistance. Additionally, operational strategies such as maintaining windows and nozzles closed during peak daytime heat can further improve indoor thermal stability while minimizing energy consumption.

Beyond the immediate implications for building design, this study reinforces the broader significance of insulation in reducing energy demands and advancing sustainability objectives. By effectively lowering heating and cooling loads, strategic insulation deployment contributes to environmental conservation efforts and enhances overall building performance. Future research should focus on evaluating the long-term durability and thermal resistance of various insulation materials under real-world conditions, conducting comprehensive lifecycle cost analyses, and exploring the integration of renewable energy systems, such as solar photovoltaic panels and geothermal heating, into holistic building solutions.

Combining cutting-edge insulation technologies with renewable energy sources presents a promising pathway toward achieving energy-efficient, resilient, and self-sustaining built environments. In conclusion, this study underscores the pivotal role of strategic insulation design in enhancing thermal comfort, reducing energy consumption, and promoting environmental sustainability. It offers valuable insights for researchers, architects, and policymakers seeking to develop innovative solutions that align with global energy efficiency and climate resilience goals.

Ethical statement

The author declares that this document does not require ethics committee approval or any special permission.

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Conflict of interest

The author declares no conflict of interest.

Authors' Contributions

A.Ç.K: Methodology, Conceptualization, Investigation

C. K: Investigation, Writing - Original draft preparation, Investigation

H. E: Conceptualization, Methodology, Supervising

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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