SJAST Journal
Multidisciplinary : Open Access Journal

Date of publication: April 24, 2025.

Evaluating the Sensitivity of Air Infiltration Rates on Envelope Thermal Insulation Performance

Azzam H. Alosaimi[1]
[1]Civil and Architectural Engineering Department, Engineering and Computer Science College, Jazan University, Jazan, KSA
Corresponding author: Azzam H. Alosaimi (e-mail: aalosaimi@ jazanu.edu.sa).

ABSTRACT High energy demands and greenhouse gas emissions have increased globally, prompting the development of energy-efficiency frameworks, legislation, and housing approvals. Due to extremely hot climatic conditions, Saudi Arabia is a primary energy producer and consumer. According to the Saudi Efficiency Center, cooling energy accounts for about 70% of the residential sector's energy demands. Although the government has issued building codes to improve overall energy efficiency and mandated the building envelope's thermal insulation, insulation performance may vary significantly when infiltration rates are not adequately evaluated. The effect of the air infiltration rate on thermal insulation performance in building envelopes is a critical factor in reducing energy demands and carbon emissions. Therefore, this study evaluates the effect of the air infiltration rate on the performance of various types of thermal building insulation using the EnergyPlus simulation tool. The findings indicate that an increased infiltration rate lowers thermal insulation efficiency and raises the indoor air temperature. Positive linear correlations were detected between an increased infiltration rate and insulation efficiency in the Jazan region, regardless of the season and insulation type. This research emphasizes the need to apply effective air sealing and waterproofing to reduce heat gains and mitigate the effect of the infiltration rate on thermal insulation performance.

INDEX TERMS Airflow Rate, Energy Efficiency, Infiltration Rate, Sensitivity Analysis, Thermal Insulation.

I. INTRODUCTION

Its vast petroleum reserves heavily influence Saudi Arabia's (SA) economy, positioning it as a world-leading oil producer and exporter. This dominance in oil production has played a central role in shaping the nation's energy policy and economic developments. As a significant player in the Organization of the Petroleum Exporting Countries (OPEC), SA holds substantial sway over global oil markets. Moreover, SA's economy and energy infrastructure rely heavily on oil, constituting 65% of the nation's total energy output, with natural gas comprising 35% [1].

The kingdom's heavy reliance on oil as a significant source of energy production and consumption has contributed immensely to massively rising carbon emissions, such as carbon dioxide (CO_2). According to data from the International Energy Agency, SA was the sixth largest emitter of CO_2 from fossil fuel combustion in 2019, at approximately 582.5 million metric tons. These increased emissions released large volumes of CO_2 and greenhouse gases into the atmosphere, significantly contributing to global warming. The upward trend in greenhouse gases has intensified the pressure on natural resources.

The reliance on oil in SA is apparent in many sectors, including buildings, transportation, industry, and electricity generation. The country's substantial oil refining capacity and petrochemical industries reinforce its dependence on oil-based energy (International Statistics and Analysis, 2019). Fig. 1 presents the primary energy production and consumption trends of the Middle Eastern nations, highlighting the position of SA as a leading producer and consumer since 2009.

In SA, buildings account for about 36% of the country's total electricity energy use [1], with the residential housing sector representing about 50% [2]. Population growth, a hot climate, and extensive air conditioning have driven this excessive energy consumption. The 36% energy demand from buildings primarily comprises cooling energy. In the residential sector, cooling energy accounts for nearly 70% of total energy consumption [3].

SJAST Journal
Multidisciplinary : Open Access Journal

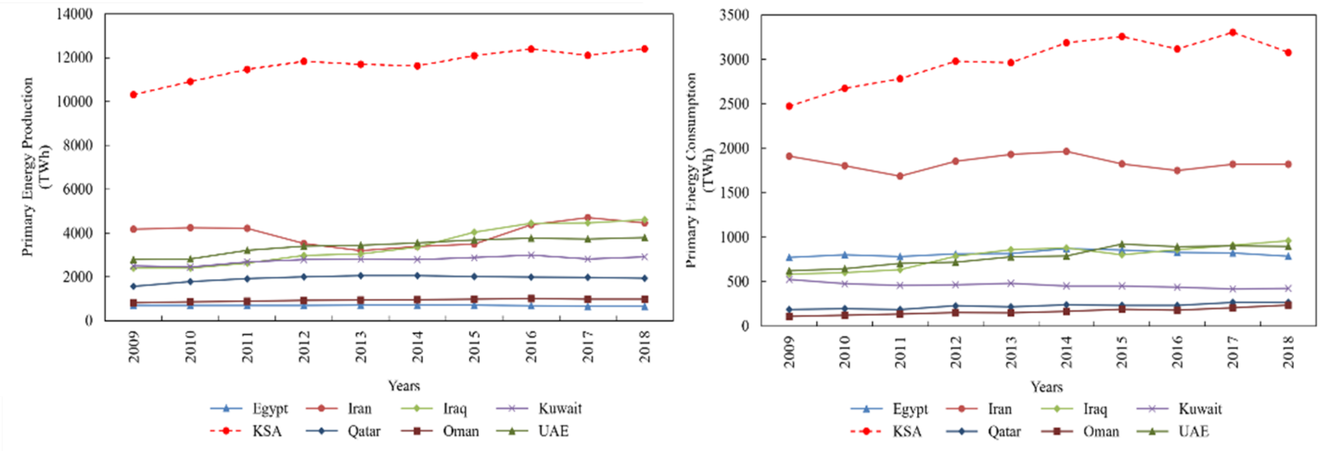

FIGURE 1. **Primary energy production and consumption of Middle Eastern countries (chart from [5]).**

In addition, SA is interested in diversifying its energy portfolio to progress toward energy-efficiency targets. Further, SA is committed to reducing its CO_2 by 2030 to meet the international minimum requirements set by the Paris Agreement in 2014, documented by the National Determined Contributions of the United Nations Framework Convention on Climate Change [4]. Hence, SA has addressed energy efficiency in various sectors to reduce energy demands and transition to a diverse and sustainable economic future.

In 2016, the Saudi Vision 2030 initiative was declared to diversify the nation's dependence on petroleum by promoting alternative energy sources, including renewable energy, such as solar and wind. These efforts align with global trends toward sustainability and environmental responsibility, highlighting the importance of energy-efficiency measures (e.g., effective insulation) in reducing the electricity energy demands of buildings.

A critical strategy for reducing the energy demands of buildings is to enhance the thermal insulation of their envelopes by creating a more effective barrier between indoor and outdoor environments. Improved insulation diminishes heat transfer and reduces energy demands on cooling systems. The improvement in insulation contributes to improved energy efficiency, enhances indoor comfort, and reduces energy costs [5].

Air infiltration significantly contributes to increased heat transfer and energy demand from the unintentional flow of hot air into buildings through cracks, gaps, and other openings in the building envelope [6]. Air infiltration remains an unexplored factor that necessitates further research. Neglecting the infiltration rate is concerning because it is crucial in determining a building's energy efficiency and overall performance. It also influences the performance of thermal insulation and may lower its efficiency.

Thermal insulation efficiency may perform differently for various infiltration rates, and the payback periods could be inaccurate. Despite its importance, the lack of research on air infiltration in SA is notable. Studies have suggested that air infiltration contributes significant heat gains in building energy use, CO_2, and electrical costs [5]. Thus, a research gap exists, particularly concerning Jazan City.

II. LOCATION AND CLIMATE

Jazan City in southwestern SA spans approximately 13500 km² and includes 29 historic districts and approximately 4000 villages. Fig. 2 shows a map of the Jazan region. Jazan's port is the third largest SA by capacity, a central entry point for imports to the southwestern region, and a significant transit hub.

Jazan's climate is strongly influenced by its proximity to the Red Sea, with high humidity levels averaging 68% throughout the year, peaking at 74% in January and dropping to 66% in August. The average high temperature reaches 38.5°C in summer and 30°C in winter, whereas the average low is 29°C in summer and 21°C in winter. Prevailing winds come from the west to the south at an average speed of 12 km/h [7].

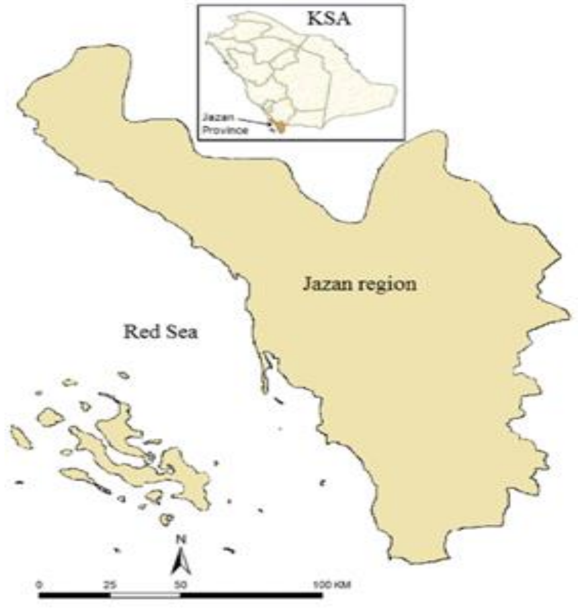

FIGURE 2. **Jazan City, Saudi Arabia [7].**

The unique climatic conditions of the Jazan region affect the performance of standard thermal insulation and air-sealing measures that reduce building energy demands. This problem requires region-specific specialized solutions to address these climatic conditions. Despite implementing building codes and rapidly expanding Jazan's infrastructure, energy-efficient retrofitting measures are necessary to reduce building energy demands and lower CO_2 emissions.

III. THERMAL INSULATION

Thermal insulation of the envelope refers to materials and techniques that reduce or prevent heat transfer through the building envelope. Thermal insulation of buildings has become increasingly important in SA due to its hot climate and growing energy demands. Recent research on thermal insulation in building envelopes has focused on optimizing its type, thickness, and placement to maximize energy efficiency. A standard method for calculating insulation thickness in these studies is the degree-day analysis, measuring the energy required to maintain a consistent indoor temperature based on outdoor temperature fluctuations [8].

[9] explored critical factors influencing the energy demand of the residential sector, such as weather conditions, dwelling types, building envelopes, and air conditioning systems. They [9] analyzed monthly electricity consumption for 115 dwellings in Dhahran in the eastern province of SA in 2012. The dwellings included 62 apartments, 28 villas, and 25 traditional houses. The study found that 50% of apartments and over 75% of traditional houses did not have thermal insulation. This finding is significant because SA has used insulation for over 20 years. However, uncertainties remain regarding the influence of infiltration rates on the most effective insulation types.

[10] applied the EnergyPlus simulation tool to evaluate the effect of building envelope designs on the energy efficiency of residential buildings in SA. Their findings indicated energy savings ranging from 22.7% to 39.5% in distinct climatic regions. The study highlighted that the wall's thermal mass was particularly effective in Abha's temperate climate, whereas the least energy savings were observed in Jeddah. Jeddah has extremely hot and humid environmental conditions that may have altered thermal insulation performance due to the higher moisture content in the air. Substantial diurnal temperature fluctuations significantly enhanced the insulation efficiency.

[11] and [12] identified that over 65% of the annual energy consumption in non-insulated villas in hot and arid regions (e.g., Qassim) could be attributed to air conditioning, representing a significant portion of the electricity usage in SA households. Considering that the residential sector consumes 50% of the total energy in the building sector, improving its energy efficiency is imperative. Although previous efforts have primarily concentrated on enhancing the efficiency of electrical appliances, an increasing need exists to evaluate potential improvements in thermal performance and building envelope design.

Other studies have emphasized the importance of climate-specific strategies for improving building energy efficiency. For instance, [13] demonstrated that integrating thermal insulation in the building envelope significantly reduces cooling loads in hot climates. Similarly, [14] found that using reflective materials and proper shading devices promotes substantial energy savings in arid regions. These studies and the research by [10] highlight the critical role of tailored building envelope solutions in optimizing energy performance across diverse climatic conditions.

[15] highlighted the requirement of controlling condensation in building envelopes in SA's hot-humid environment. They observed that condensation concerns could substantially affect the longevity and thermal performance of wall materials because accumulated moisture in building materials reduces insulation effectiveness and increases cooling loads. The study indicated that moisture control measures (e.g., vapor barriers and permeable materials) are critical to preserving energy efficiency and interior thermal comfort in these settings.

Given the limited data on condensation in building envelopes in the Jazan region, studies from comparable locations with similar environmental conditions were reviewed. For instance, [16] explored condensation effects in building envelopes in hot and humid climates. They [16] studied wall assemblies in the humid tropical islands of the South China Sea and observed a significant reduction in thermal insulation efficiency due to increased moisture content. Furthermore, [17] identified a direct correlation between elevated moisture levels and wall materials' decreased thermal resistance (i.e., the R-value). These findings support the importance of moisture control strategies in building design to maintain indoor comfort and energy efficiency in humid regions.

The literature review highlights increasing evidence supporting the need for thermal insulation in buildings across SA to enhance energy efficiency. However, a notable gap in the research concerns the Jazan region, which is particularly important given its unique climatic conditions. These conditions significantly differ from those of other SA regions and may influence the effectiveness of thermal insulation.

Moreover, the latest version of the Saudi Building Code (SBC) mandates the application of thermal insulation to building envelopes to lower thermal conductivity and reduce heat transfer [18]. While this regulation is promising, further investigation is required to understand how varying infiltration rates affect the performance of insulation materials in various climates.

The most common thermal insulation types in the local Saudi market include board, batt, cellular glass (CG), fiberglass (FG), and polyurethane (PO), which are summarized and compared. These insulating materials were selected because they are widely available and commonly used in the Saudi market. Each material had specific benefits consistent with local construction methods and climatic circumstances, making them suitable for assessing building energy performance in SA [5]. The insulation thicknesses applied in this study (i.e., 25, 50, 75, and 100 mm) were determined based on practical considerations in SA's building sector because typical insulation thicknesses for various building types are generally within this range. The specified thicknesses enabled a variety of energy performance outcomes, including cost-effective and high-performance scenarios [19].

Fig. 3 represents a comparative analysis of thermal insulation types. The board and poly materials had the lowest thermal conductivity (0.03 W/mK) and the highest R-values (43 and 35 m²·K/W, respectively), with superior insulating properties. The board had a 40 kg/m³ density and a heat capacity of 1400 J/kg·K, so it was lightweight yet effective. In contrast, batt had the highest conductivity (0.05 W/m·K) and the lowest R-value (19 m²·K/W), so it was the least effective insulator among the compared materials. The CG and FG materials exhibit moderate conductivity, material resistance (R-value), density, and heat capacity values, so their performance falls between the board and batt materials. Although insulation significantly reduces the infiltration rate and heat transfer between a building's interior and exterior environments and makes buildings more airtight, its thermal performance may be compromised.

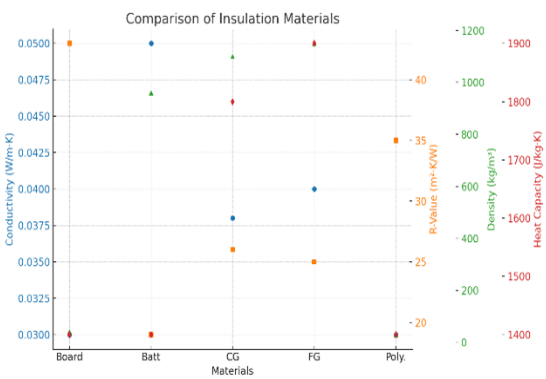

FIGURE 3. **Insulation material details and comparison (Data collected from multiple sources [5], [9], and [10]).**

IV. INFILTRATION RATE

The infiltration rate refers to the air-leakage rate at which outside air (unconditioned) enters a building through unintended openings (e.g., cracks, gaps, and other penetrations) in the building envelope. It measures how much air can be changed in 1 h and is expressed by the air changes per hour (ACH). The building infiltration rate is critical for evaluating indoor conditions to promote energy efficiency, indoor air quality, and thermal comfort [20].

The envelope cracks create an air-leakage area, allowing unconditioned air to flow from outdoor to indoor environments and mix with conditioned air. Therefore, high infiltration rates can lead to increased energy consumption, as cooling systems work harder to maintain the desired indoor temperature. Additionally, infiltration can influence occupant comfort and health by introducing pollutants, allergens, and humidity into the indoor environment [20].

Infiltration arises due to a pressure difference ($\triangle P$) across the envelope caused by geometrical, physical, and environmental variables. Geometrical variables include the building design, area, shape, and volume. Physical variables are the physical properties of the constitution materials, such as thermal conductivity and thickness. Environmental variables include weather variations, such as the dry bulb temperature, wind speed and angle, and sky cover. Infiltration can also result from construction defects, poor sealing, or aging materials, per [5].

Building air leakage is closely correlated with construction methods. According to [20] and [21], the wall construction type is a critical factor in the energy efficiency of retrofitting approaches. The UK commonly uses load-bearing walls with timber framing. When plasterboard is mounted using adhesive dabs, it can create interconnected air-leakage pathways throughout the building, making it difficult to achieve adequate air sealing. A wet-plastered masonry wall can be significantly more airtight than a dry-plastered one [21].

In contrast, timber-framed walls are prevalent in northern Europe and North America. [20] analyzed data from the Building Research Establishment database, a UK-based organization, and indicated that timber-framed buildings are generally more airtight than masonry buildings. However, this difference was less significant when considering the age of the houses because most UK timber-framed homes are relatively new constructions.

In SA, residential buildings typically employ concrete, blocks, clay bricks, and stone construction materials, while Portland cement is the predominant building construction material. Concrete is made by mixing cement, water, coarse aggregate, and sand, providing a robust and durable solution for building structures, foundations, and other construction elements. The prevalence of these materials reflects the need for sturdy and resilient construction in the region's challenging climate and environmental conditions. Generally, concrete has a low infiltration rate due to its dense structure, providing an effective barrier against air leakage [22]. However, concrete buildings can still be infiltrated by air leaks in joints, cracks, and improperly sealed connections with other building components (e.g., doors, windows, and utility penetrations).

Despite the increasing research on energy efficiency in buildings in SA, a significant knowledge gap remains regarding infiltration rates in residential buildings. Infiltration critically affects heat gains, particularly in hot climates. Uncontrolled air leakage can significantly increase cooling loads and lower indoor thermal comfort.

The current literature has identified several common sources of air leakage, including building materials [20], thermal insulation [23], insulated concrete [24], windows and doors [25], air barriers [26], and garages [27]. However, specific studies on quantifying and mitigating infiltration rates in Saudi residential buildings are limited. Therefore, considering the extreme temperatures and heavy dependence on air conditioning for thermal comfort, understanding and addressing infiltration to optimize energy use is imperative.

Air infiltration substantially influences insulation performance due to air leakage through building envelopes. Air leakage may compromise the thermal conductivity of insulation materials. According to [28], air infiltration raises heating and cooling demands and changes moisture levels, leading to material deterioration and poor building efficiency. For example, airtight construction, such as passive house standard buildings, highlights the necessity of reducing air infiltration to achieve optimal energy efficiency and thermal comfort [29].

Furthermore, climate-specific models reveal that differences in the air infiltration rate considerably influence energy demand. For example, increased air infiltration in lightweight and heavyweight construction emphasizes the importance of effective air-tightness techniques [29].

A few studies have evaluated the air infiltration rate in SA, such as those conducted by [30], [31], and [5]. For instance, [30] analyzed air-leakage patterns and behaviors in single-family homes with central air conditioning. They identified sources and rates of air leakage, assessed their effects on energy performance, and provided insight to improve the efficiency of central air conditioning systems. The findings offered strategies for enhancing air tightness in buildings and energy efficiency in similar residential settings. However, the study contributions could have been more significant if they had considered a larger sample size and included energy simulation to allow for more generalizable results and a better understanding of the implications of air leakage on energy performance across a broader range of homes.

[31] studied air infiltration rates in residences in SA, finding substantial disparities due to differences in architectural designs, climates, and construction processes. In Jeddah, infiltration rates have frequently been estimated to be 1 ACH for simulation purposes, with some studies reporting 0.32 and 0.35 ACH values due to exfiltration from central heating, ventilation, and air conditioning (HVAC) systems. Moreover, [31] revealed diverse values in several types of buildings and conditions and highlighted the prospect of energy savings when achieving SBC's stricter guidelines of 0.2 ACH. These findings indicated the need to consider air infiltration elements in insulation construction and energy modeling to increase overall building efficiency.

[5] developed a model to predict the infiltration rate and associated heat loss for the residential sector in SA using MATLAB software. The model predicts airflow rate values more consistent with the SBC standard of 0.2/h, as opposed to the higher values of 0.8/h commonly reported in the literature. [5] demonstrated that heat loss in Saudi homes could reach up to 37.3 MW·h, with a median value of 1.97 MW·h. However, the study did not explore the relationship between infiltration rates and the performance of envelope thermal insulation. While the study provided valuable insight into energy retrofitting measures and infiltration rate values for the housing sector, it did not explore the effect of the infiltration rate on thermal insulation performance in the Jazan region. Hence, this clear research gap indicates the need for further investigation.

A. INFILTRATION RATE MEASUREMENTS

Infiltration rates in buildings can be evaluated via actual measurements or modeling techniques. The most common approach is applying actual measurements using the blower door test, which installs a specialized frame and fan at the main entrance of a building with all internal openings sealed. The fan creates a pressure difference between the indoor and outdoor environments by extracting air from the interior, and the resulting pressure differential (ΔP) is measured to determine the infiltration rate [32].

The University of Nottingham developed a more recent accurate measuring tool, the pulse test, to measure air leakage. Unlike the blower door test, typically installed at the main entrance, the pulse test is a portable device placed in the center of a dwelling. After sealing all openings, the device calculates the airflow rate via a dynamic measuring process to provide additional data on the interior temperature, humidity, and pressure differences [33]. As it operates in a single pulse, the pulse test does not require blocking building doorways to create a continuous airflow (using a fan). Thus, the pulse test method is less intrusive, simpler, and faster. The UK government recently accepted it for measuring air tightness in buildings because it simplifies and accelerates air-tightness testing. However, the pulse test cannot identify specific air-leakage paths due to its general dynamic measurement technique, unlike the blower door test, which can locate areas of significant air leakage.

Both approaches have been widely employed to measure building air leakage, each with advantages and disadvantages. The blower door test has been frequently used for precise, quantitative assessments of air tightness in buildings by pressurizing and depressurizing a structure to measure the airflow to maintain a constant pressure. Nonetheless, variations in temperature, building volume, and pressure boundary conditions can affect the test when they are not adequately considered. In contrast, the pulse test is a more straightforward, quicker alternative that measures pressure decay in a building over time, with quick leakage rate estimations. Although less intrusive and effective for recognizing significant leaks, some variables (e.g., building configurations) may reduce the accuracy of the pulse test. It is also less reliable for tight structures and minor leaks demanding greater precision [33].

B. INFILTRATION RATE MODELING

Modeling building infiltration rates is critical for evaluating energy efficiency, indoor air quality, and thermal comfort by assessing air leakage through the building envelope due to gaps, cracks, and other openings. Energy simulation software packages, such as Department of Energy (DOE-2) and EnergyPlus, include features for modeling infiltration rates. These simulation tools allow users to set values based on blower door test results, building details, and other data sources [34].

These tools can simulate how infiltration affects the thermal insulation performance by considering pressure differentials, environmental conditions, and other factors. Thus, users can model various scenarios and evaluate the effects of infiltration on indoor air temperature (IAT) and indoor contamination. These simulation tools also support informed decisions on optimizing energy efficiency and improving thermal comfort, making infiltration rate modeling an essential component in designing and retrofitting buildings for better performance [5].

The two energy-building simulation types are *active* and *free-run* simulations. Active simulations consider building system operations (e.g., heating and cooling), whereas free-run simulations refer to energy modeling without active building systems, such as heating and cooling units. The free-run simulation approach assesses how a building behaves under natural conditions without artificial climate control, providing insight into the passive design, thermal mass effects, and influence of building envelope characteristics on indoor thermal comfort [35].

Energy simulation software can be instrumental in guiding building design, retrofitting projects, and energy-efficiency measures. With the ability to simulate the influence of infiltration, users can identify critical areas for improvement, such as sealing gaps, enhancing insulation, and implementing controlled ventilation systems. This approach reduces energy consumption and creates a more comfortable and healthier indoor environment.

Evaluating air infiltration rates with actual measurements is the most accurate approach and typically involves specialized equipment, such as blower door tests or pulse tests. However, modeling techniques offer a practical alternative when direct measurement is impossible due to a lack of data or limited access to these tools.

V. METHOD

This study developed a free-run simplified building model to assess the effect of varying infiltration rates on the performance of various thermal insulation types used in building envelopes. This research employed a one-parameter-at-a-time approach to analyze IAT using EnergyPlus simulation software. EnergyPlus was employed for this study due to its robust capabilities for building energy performance analysis. This software offers a comprehensive insight into the envelope heat transfer performance. It supports the dynamic modeling of air infiltration by calculating the heat-transfer time lag and damping effects to reflect real-world conditions, accounting for the outdoor air temperature, wind speed and angle, and ΔP [34].

A. BUILDING MODEL

The energy model was developed to simulate the passive behavior of the actual building space, allowing for a concentrated analysis of how infiltration rates affect the performance of thermal insulation types in the Jazan region. The modeling approach assesses the fundamental influence of air infiltration to provide a clear understanding of the passive performance of thermal insulation types. The study objective was to determine how variations in the infiltration rate influence thermal insulation performance. Therefore, the model eliminated building systems (e.g., cooling, lighting, and equipment) to isolate the effects of the infiltration rate on insulation performance.

The selected building model was a villa with a total floor area of 525 m^2. The walls were constructed with 20-mm plaster on the interior and exterior surfaces, with a 150-mm concrete hollow block. The roof consisted of 10-mm built-up roofing, a 200-mm concrete roof slab, and 13-mm plaster on the inside. The floor comprised ceramic tile with a 100-mm concrete slab on the grade. The windows included single-clear glazing with wood frames, and the window-to-wall ratio was 13%. The air infiltration rate was 0.8 ACH [12]. Table I summarizes the building model details.

TABLE I
BUILDING DETAILS FROM [12]

Building model	Villa details
Floor area	525 m^2
Wall construction	20-mm plaster outside and inside, 150-mm concrete hollow block
Roof construction	10-mm built-up roofing, 200-mm concrete roof slab, 13-mm plaster inside
Floor construction	Ceramic tile, 100-mm concrete slab on grade
Glazing	Single clear (wood frame)
Window-to-wall ratio	13%
Air infiltration	0.8 ACH

The infiltration rate set by [12] was derived from the minimum cooling requirements of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). However, this value might not be sufficiently precise for predictive modeling. [5] evaluated the sensitivity of infiltration rates on energy modeling outcomes, finding that it substantially influences heat-transfer calculations for uninsulated building envelopes. However, the broader effects of infiltration rates on building envelope configurations with various thermal insulation materials remain unexplored. Consequently, this study investigated the impact of infiltration rates on envelope thermal insulation in a hot and humid region.

All exterior surfaces, including solar radiation and wind, were exposed to weather variations. The weather data for the Jazan region were obtained from EnergyPlus weather data (i.e., from the .epw files). The data were selected over other types because they represent the actual context.

The study investigated five types of thermal insulation: board, batt, FG, CG, and PO. The insulation thicknesses were systematically increased to 25, 50, 75, and 100 cm, labeled 1, 2, 3, and 4, respectively. For instance, board insulation with a thickness of 50 cm was denoted as Board 2. The insulation was applied to the exterior surface because it performed better than interior surface applications [5]Air infiltration rates were incrementally increased (i.e., 0, 0.25, 0.50, 0.75, and 1 ACH) for each insulation type to examine the effect on the IAT.

The simulation was conducted on two highly different days to observe the differences in thermal insulation performance: January 1, representing the coldest day in winter, and August 1, representing the hottest day in summer. This selection was critical to capture the hourly effects on the IAT by varying the thermal insulation type and thickness. These two days were selected to reflect the extremes of seasonal environmental conditions using data from the typical meteorological year for the researched region. This approach was similar to a recent research [7] approach that sought to decrease computational requirements while concentrating on border circumstances, where building performance is most challenging. The simulation approach to developing the base model required a validation stage of the outer surface temperature and IAT to ensure it behaved similarly to the original model.

VI. VALIDATION

A. OUTSIDE TEMPERATURE VALIDATION

The mean outside surface face temperature (OSFT) is an essential metric for evaluating the insulation performance of a building envelope in an energy model. This measure indicates how much heat the outer surface receives from solar radiation and the ability of the surface to store, resist, and transfer heat. The OSFT was selected for the validation because it directly reflects the heat influence from solar radiation on the external surfaces of the thermal envelope.

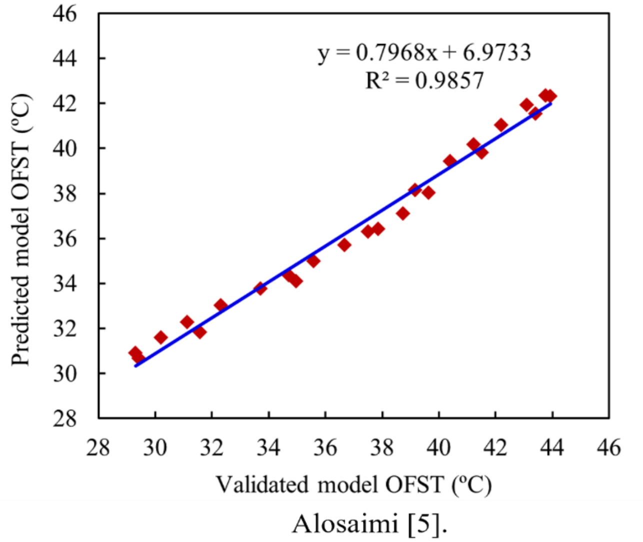

FIGURE 4. **The outside surface face temperature of the proposed model and [5] energy model.**

The model was simulated hourly on July 1 to examine the thermal envelope performance during an extremely hot day. The mean OSFT from the proposed base model was compared with a previously validated model by [10], [12], and, more recently, [5]. Fig. 4 indicates a strong agreement with a performance coefficient (R2) of 0.98, suggesting that the proposed model effectively captures the critical aspects of the building envelope's thermal behavior. This measure indicates the reliability of the heat transfer and insulation performance simulation.

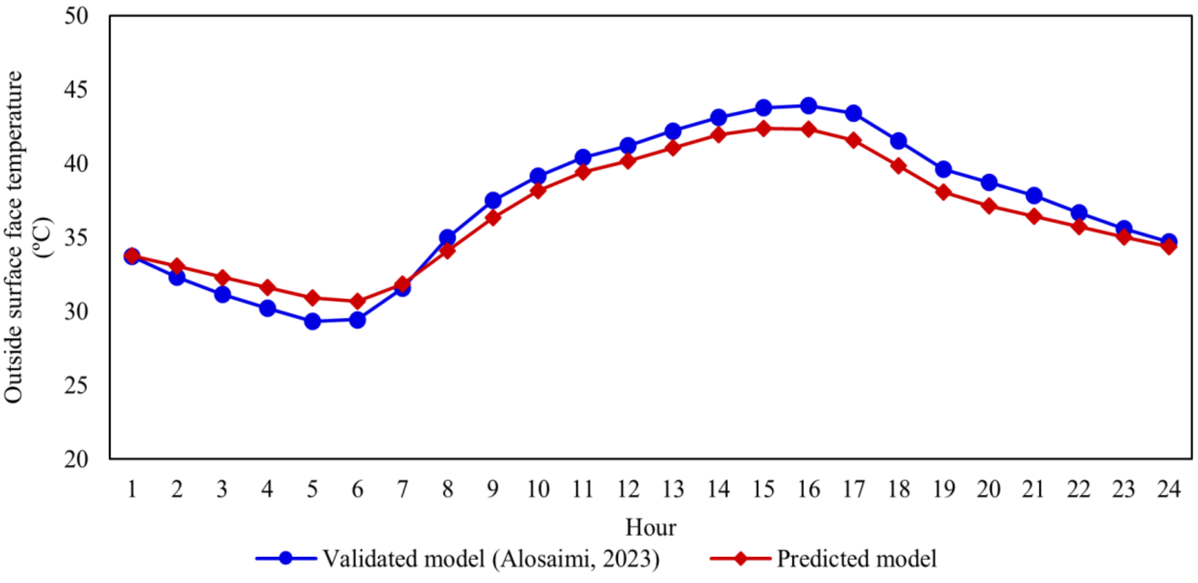

FIGURE 5. **Hourly outer surface face temperature for the proposed and [5] energy models.**

Fig. 5 describes an hourly OSFT comparison of both models, which performed similarly with similar peak hours. The peak OSFT of the proposed model was 42.3°C at 16:00, whereas the [5] model indicated a peak of 43.9°C. The lowest OSFT of the proposed model was 30.6°C at 18:00, compared to 29.3°C at 17:00 in the [5] model. Table II summarizes both models' descriptive statistics.

TABLE II
DESCRIPTIVE STATISTICS OF THE ENERGY MODELS

Building model	[5]	Proposed model
Mean	37.2	36.6
SE	1.0	0.8
Median	37.7	36.4
SD	4.8	3.9
Variance	23.2	15.0
Kurtosis	-1.2	-1.3
Skewness	-0.2	0.1
Range	14.6	11.7
Minimum	29.3	30.7
Maximum	43.9	42.4
Sum	891.9	878.0
Count	24.0	24.0
Confidence level (95.0%)	2.0	1.6

B. INDOOR AIR TEMPERATURE VALIDATION

The IAT calibration displayed similar trends between the proposed model in this study and [5] previously validated model. Fig. 6 highlights the correlation between the models with an R^2 value of 0.98. This finding is significant because it indicates that the model predicts values similar to actual building values. Fig. 7 highlights the hourly IAT of both models, indicating similar trends and behaviors during the hourly simulations. Both models have identical IAT peak hours at 18:00 before sunset, which is explained by the high thermal mass of the building and the time delay of heat transfer from the exterior to interior surfaces. The IAT validation exhibited a similar IAT between the previously validated and proposed models. This finding reveals that the proposed model in this study can produce similar IAT values or outputs as the validated model and allows for evaluating the influence of the infiltration rate on the thermal insulation performance of the envelope.

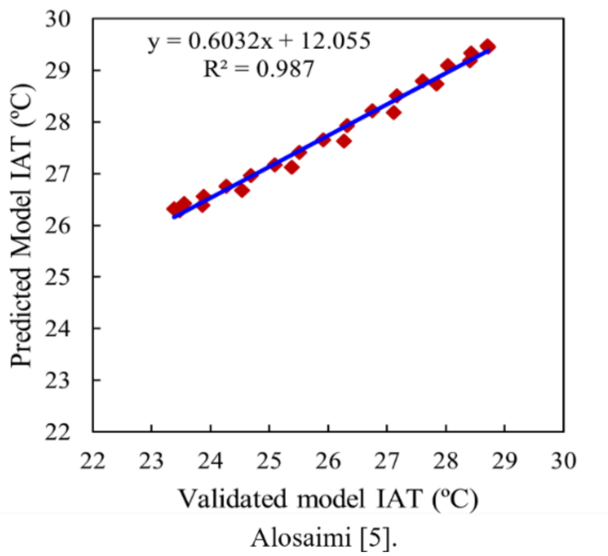

FIGURE 6. **Indoor air temperature of the proposed model and [5] energy model.**

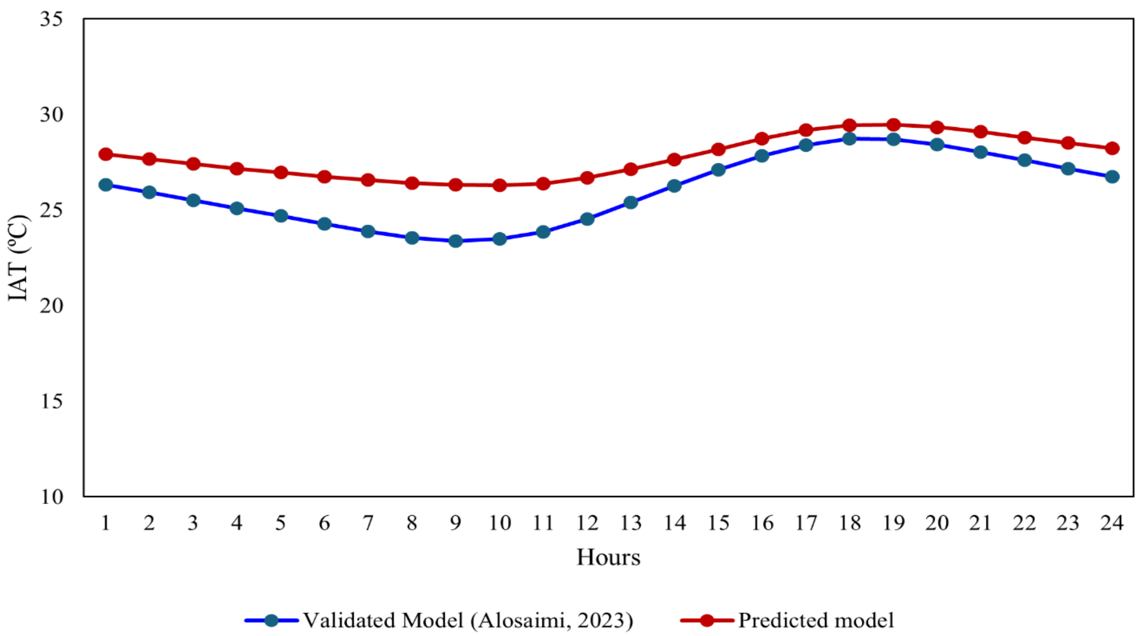

FIGURE 7. **Hourly indoor air temperature (IAT) of the proposed model vs. the validated model by [5].**

VII. RESULTS

This study aims to determine how variations in the infiltration rate influence thermal insulation performance in the hot and humid region of Jazan.

A. THERMAL INSULATION

Applying distinctive types of thermal insulation to the building envelopes exhibited varying effects on the IAT of the proposed base model during winter and summer. The predictions indicated that January 1 had a lower IAT, whereas August 1 required more cooling energy due to higher heat loads. Fig. 8 describes the performance and effects of the insulation type and thickness on the IAT. The dashed orange line presents the mean IAT in winter of the base model (without thermal insulation), whereas the dashed blue line indicates the mean IAT during summer of the base model. Most insulation types increased the heat transfer from the exterior to interior environments, resulting in a higher IAT. This unexpected effect was likely due to the high humidity levels and extreme weather conditions in SA. However, 50-cm thick CG insulation (i.e., CG2) lowered the mean IAT from 23.2°C to 23°C in January and from 23.5°C to 23.2°C in July due to its impermeability to water and water vapor. Hence, certain insulation types effectively mitigate heat transfer despite challenging climatic conditions. In contrast, applying 100-cm polyurethane insulation (i.e., PO4) maintained the IAT of the base model at 23.2°C in January and 23.5°C in July. These results suggest that various insulation materials and thicknesses significantly influence the IAT and building energy demand for cooling.

B. INFILTRATION RATE

Infiltration rate variations and the thickness of five types of thermal insulation significantly influenced the IAT. Fig. 9 indicates that the mean IAT rises across all insulation types as the infiltration rate systematically increases. This trend occurs because a higher infiltration rate allows more hot and humid outdoor air to enter the building, raising the IAT. The effects were most pronounced in environments where temperature differentials between indoor and outdoor spaces were significant, which is often in SA's climate.

[12] assumed an identical air infiltration rate for three residence types (i.e., villas, apartments, and traditional houses) of 0.8 ACH. However, this assumption might have led to inaccurate results, especially considering the various building types and construction materials.

[31] revealed that the infiltration rates of Saudi residences could be 1 ACH for modeling and simulation evaluations. In contrast, other studies have demonstrated that infiltration rates could be 0.32 to 0.35 ACH. However, they did not capture the effects of varied infiltration rates on energy performance in the Jazan region. [5] predicted housing infiltration rates of the total housing stock in Saudi in various regions and revealed that the mean air infiltration rates were 0.02 and 0.24 ACH for apartments and villas, respectively. Moreover, [5] found a mean infiltration rate in Jazan dwellings of 0.05 ACH. This research has applied a range of infiltration rate values to capture the effects on the IAT.

The results indicate that controlling infiltration rates is critical to maintaining optimal IAT and energy efficiency, even with varying thermal insulation thicknesses. The

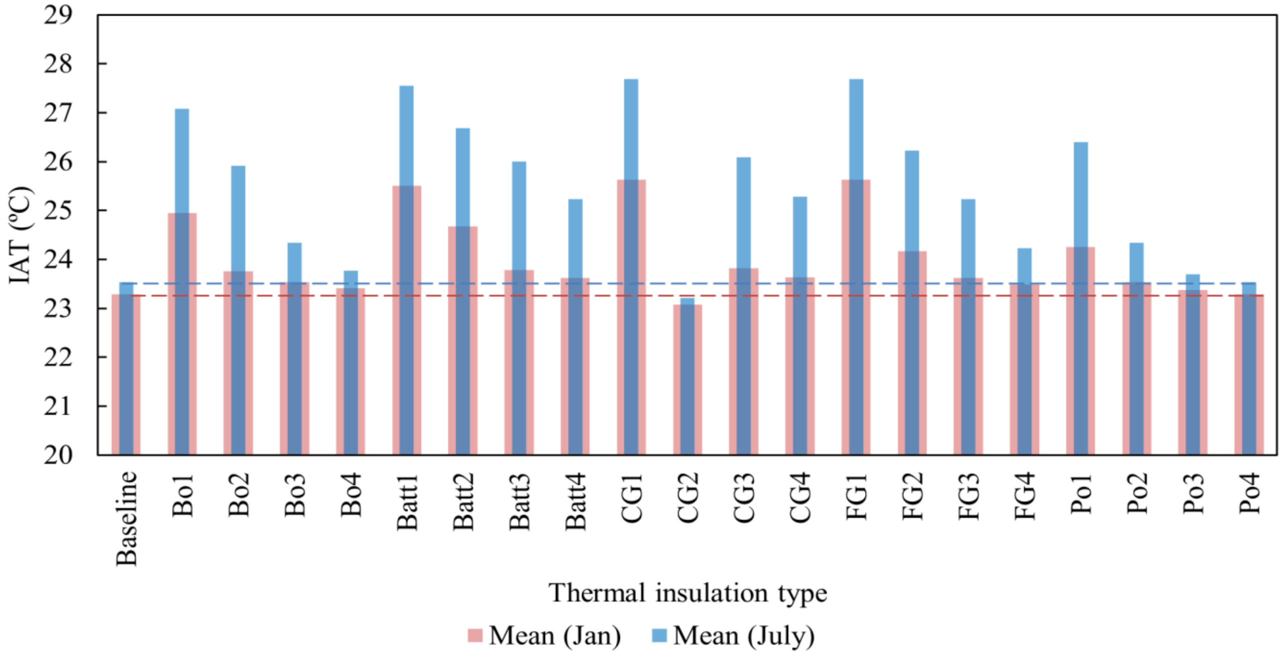

FIGURE 8. **Indoor air temperature of a building with differing thermal insulation types and thicknesses.**

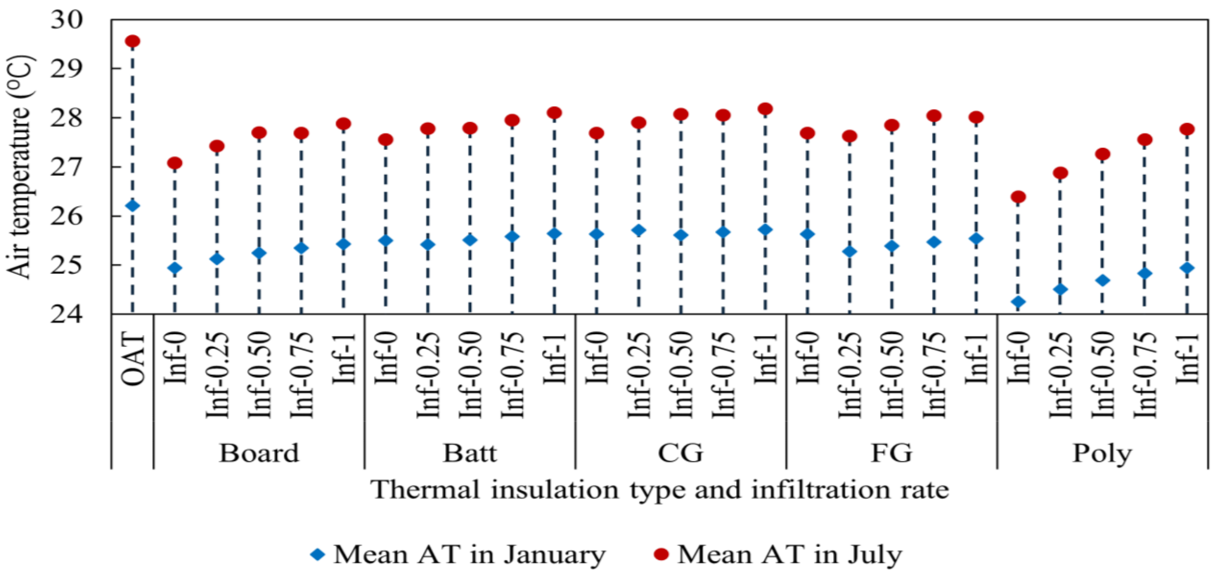

FIGURE 9. **Indoor air temperature of the building with differing thermal insulation types and thicknesses.**

findings highlight the importance of performing a sensitivity analysis to identify the correlation between the air infiltration rate and thermal insulation type and thickness.

C. *SENSITIVITY ANALYSIS*

A sensitivity analysis was conducted to identify the relationship between the infiltration rate, insulation type and thickness, and influence on the IAT. The study revealed that higher infiltration rates lead to a higher IAT, particularly under extreme weather conditions. This finding identified the complex relationship between insulation and infiltration in determining indoor thermal stability. The study highlights that, during extremely hot and humid weather, the effect of a high air infiltration rate is more severe and results in drafts, uncomfortable temperature swings, and increased energy consumption to maintain indoor thermal comfort.

Fig. 10 reveals a positive linear relationship between the mean IAT and the thermal insulation thickness. Hence, the insulation thickness increases as the mean IAT increases. Therefore, thicker insulation may retain more heat. The analysis also demonstrated that a higher air infiltration rate increases the IAT during both seasons. This effect was attributed to the greater air exchange between indoor and outdoor environments, introducing hot and humid air in summer and cooler air in winter. This process alters the thermal stability of the building, the insulation material performance, and the overall energy efficiency. The findings indicate that, as the outdoor air temperature increases, the OSFT of the building rises due to heat absorption.

VIII. DISCUSSION

This study assessed variations in air infiltration in the SA climate, enduring incredibly high temperatures, especially during summer, with notable variations between day and night. Air infiltration significantly strains cooling systems and leads to increased energy demands. This challenge is exacerbated by the critical need for effective insulation to maintain energy efficiency. Thermal insulation can lose effectiveness if air infiltration rates are high, as the ability of the insulation to stabilize indoor temperatures is compromised.

The Jazan region has a distinct climate characterized by high temperatures and humidity in summer and lower, colder temperatures in winter, with substantial seasonal change and humidity levels compared with other regions in SA. These environmental variables are significant when assessing how air infiltration and insulation effectiveness vary by region. For example, although northern regions may experience severe variations in temperature, the greater degree of humidity on the coast of Jazan can lead to unique insulation performance outcomes, particularly with moisture accumulation and material degradation. Nonetheless, regions with more arid climates, such as Riyadh, may display different infiltration characteristics.

Additionally, condensation considerably influences thermal performance, particularly in humid locations like Jazan. Condensation can raise moisture levels in building materials, reducing the insulating efficacy and accelerating material deterioration. Thus, condensation is significant in building design and insulation material selection for high-humidity locations, so condensation management is critical for preserving building envelope durability and energy efficiency over time [15] and [16].

The effect of air infiltration on thermal insulation is a significant concern because it affects energy efficiency, indoor comfort, and sustainability. Uncontrolled hot air entering buildings can undermine the effectiveness of insulation while raising energy demands and increasing the cooling system workload. Thus, studies on the air tightness of buildings and infiltration rates should be conducted with greater depth and larger building samples in diverse climate conditions in SA.

Field studies and actual measurements of infiltration rates are necessary to obtain a comprehensive understanding of the problem. Collecting data from a large sample of buildings could provide a reliable basis for future studies and assist in informed decision-making processes. This data-driven approach could help create influential measures for reducing air infiltration to enhance thermal insulation performance and improve energy efficiency.

This study found that the most suitable thermal insulation for buildings in the Jazan region is CG1. However, [5] suggested that PO4 is the optimal insulation. This discrepancy is attributed to the varying locations with higher humidity and moisture levels. A high infiltration rate allows hot air and moisture to bypass insulation layers, leading to condensation problems. Condensation is a significant problem that considerably influences the building structure, indoor air quality, thermal comfort, and energy performance. Increased condensation reduces insulation performance and introduces health concerns. Therefore, studies on condensation in buildings in the Jazan region are necessary to provide insight into how buildings can be insulated. Studies should focus on thermal bridges and areas where condensation occurs most.

The sensitivity of infiltration rates reveals the critical importance of implementing air-sealing and weather-proofing measures in building envelopes. Architects and engineers are vital in prioritizing strategies to minimize infiltration, reduce the burden on cooling systems, and enhance overall energy efficiency. Critical measures include applying air barriers, sealing gaps and cracks, and specifying insulation materials with low air permeability.

This study highlights the need for more comprehensive investigations to assess infiltration rates in building types across SA's climatic regions. These investigations should aim to identify the primary sources of air leakage, evaluate the effectiveness of existing mitigation measures, and develop guidelines for improving building airtightness.

These research findings can inform future construction regulations in SA, where energy efficiency is becoming increasingly crucial. Regulations should be applied to building commissioning to obtain a maximum infiltration rate value and ensure efficient energy use. Robust and varied values for infiltration rates should be considered according to the building type and location. The climate significantly influences the infiltration rate, so it should be considered in the building code rather than assuming the value of 0.2 ACH for all housing types and locations in SA.

IX. LIMITATIONS

Research on infiltration rates in SA faces several limitations hindering a comprehensive understanding of this problem across its diverse climates. The scope of existing studies is limited, with small sample sizes reducing their generalizability. Most research has focused on residential buildings, neglecting commercial and industrial sectors. Moreover, short-term studies have failed to capture seasonal variations in infiltration rates. Differences in construction materials, techniques, and standards across regions have further complicated the generalizability of findings. Technological and methodological constraints (e.g., inconsistent measurement techniques and limited advanced modeling tools) have also impeded accurate assessments.

Additionally, no studies have explored the interaction between infiltration rates and thermal insulation performance, which is crucial to understanding building energy efficiency. This omission highlights the importance of the current research in filling this significant gap. Addressing these limitations through more comprehensive, diverse, and technologically advanced research is essential to developing effective strategies to optimize energy efficiency in buildings across SA. Although this research adopted a one-parameter-at-a-time approach to investigate the concentrated effect of selected parameters on the IAT, a multivariate sensitivity analysis should be considered to understand how other parameters influence the IAT.

The simplified model, which eliminated active HVAC systems, lighting, and equipment, was limited because these variables significantly affect real-world energy use. Thus, the lack of these systems could limit the application of these findings to actual building settings. Future studies should include precise models of HVAC systems and other energy-consuming components to offer a more comprehensive understanding of the energy performance of a building. A dynamic model accounting for these systems would increase the accuracy and usefulness of the findings. Furthermore, it would be helpful to investigate the relationship between air infiltration, insulation, and HVAC system performance in real-world scenarios.

Furthermore, the dependence on predictions for two days (i.e., winter and summer extremes) restricted the generalizability of the findings throughout the year. During spring and fall, transitional months may have different infiltration and insulation interactions due to changing temperatures and wind conditions. Expanding the analysis to include simulations from more typical months or using an annual hourly weather dataset to enhance the findings would be promising. This upgrade could provide a more thorough understanding of the building’s year-round performance and improve the generalizability of the findings, as advocated in [36].

A more thorough seasonal study incorporating actual weather data from different months or a yearly cycle would offer more detailed information on how air infiltration and insulation perform over the year. Experimental validation with actual data from buildings would assist in corroborating the simulation output to bridge the gap between theoretical modeling and practical application. Future research could include field investigations that monitor actual infiltration rates and energy performance in buildings and allow simulation models to be calibrated for improved comprehension of the influence of insulation materials and thicknesses in real-world scenarios.

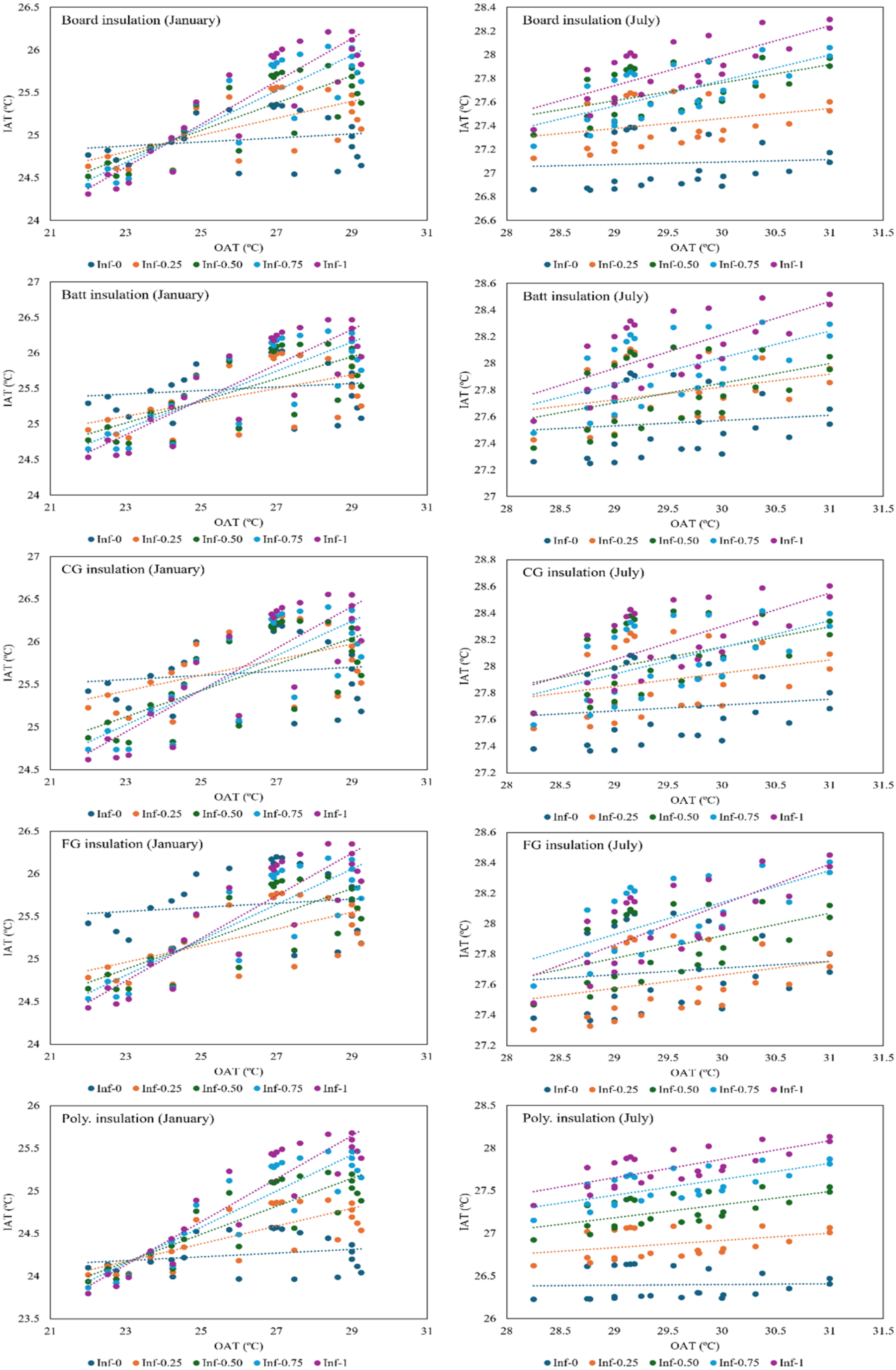

FIGURE 10. **Sensitivity analysis of the infiltration rate and insulation type and thickness on indoor air temperature.**

X. CONCLUSION

Air infiltration rates significantly affect the thermal insulation performance in building envelopes, influencing energy efficiency and indoor air quality. This study analyzed various insulation types—board, batt, FG, CG, and PO—using the EnergyPlus simulation tool. The study applied a one-parameter-at-a-time approach to explore the sensitivity to changing air infiltration rates on thermal insulation performance.

This study examined how various insulation types responded to air leakage by systematically varying infiltration rates, particularly in the hot and humid climate of Jazan. The results indicate that higher air infiltration rates reduce thermal insulation performance and increase energy demand for cooling. These findings highlight the importance of effective air sealing and airtight construction to maximize insulation material efficiency. Proper insulation and reduced air infiltration can enhance energy efficiency and indoor comfort. Air infiltration rates significantly influence thermal insulation performance in building envelopes, affecting energy efficiency, indoor comfort, and indoor air quality. The findings revealed that the Jazan region should apply more region-specific requirements for air tightness to reduce infiltration rates, lower energy demand, and mitigate envelope condensation.

Moreover, this research has important implications for national policy and economic development goals. As a significant member of OPEC and the International Energy Agency, SA is committed to adopting more energy-efficient practices. Enhancing building performance aligns with the country's efforts to reduce energy consumption while maintaining economic competitiveness. With SA's Vision 2030, prioritizing a reduced carbon footprint of the built environment, the study findings can inform policy frameworks that encourage adopting sustainable building technology and airtight construction practices.

The economic benefits of improving insulation performance and reducing energy demand for cooling are substantial to meet SA developmental visions, especially in a region with significant energy costs. Moreover, SA can make meaningful energy conservation and sustainability progress by addressing building air infiltration and insulation to ensure long-term economic gains while fulfilling its global commitments in the energy and environmental sectors.

REFERENCES

[1] M. S. Al-Homoud and M. Krarti, "Energy efficiency of residential buildings in the kingdom of Saudi Arabia: Review of status and future roadmap," J. Build. Eng, vol. 36, p. 102143, 2021.
[2] M. Aldubyan, M. Krarti, and E. Williams, "Residential energy model for evaluating energy demand and energy efficiency programs in Saudi residential buildings," Energy, vol. 195, p. 116980, Mar. 2020.
[3] A., Felimban, A. Prieto, U, Knaack, T. Klein, and Y. Qaffas, "Assessment of current energy consumption in residential buildings in Jeddah, Saudi Arabia," Buildings, vol. 9, no. 7, p. 163, 2019.
[4] D. Scott, C. M. Hall, and S. Gössling, "A report on the Paris Climate Change Agreement and its implications for tourism: Why we will always have Paris," J. Sustain. Tour, vol. 24, no. 7, pp. 933–948, 2016.
[5] A. Alosaimi, "Optimising the energy performance of the residential stock of the Kingdom of Saudi Arabia by retrofit measures." University of Nottingham, 2023.
[6] M. H. Sherman, Air Infiltration in Buildings, Ph.D. thesis, University of California, Berkeley, Jan. 1980.
[7] H. T. Abd El-Hamid et al., "Detection of environmental degradation in Jazan region on the Red Sea, KSA, using mathematical treatments of remote sensing data," J. Remote. Sens., vol. 2, no. 4, pp. 183–196, 2019.
[8] A. Ucar and F. Balo, "Effect of fuel type on the optimum thickness of selected insulation materials for the four different climatic regions of Turkey," Appl. Energy, vol. 86, no. 5, pp. 730–736, 2009.
[9] F. Alrashed and M. Asif, "Trends in residential energy consumption in Saudi Arabia with particular reference to the Eastern Province," J. Sustain. Dev. Energy Water Environ. Sys., vol. 2, no. 4, pp. 376–387, 2014.
[10] A. Alaidroos and M. Krarti, "Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia," Energy Build., vol. 86, pp. 104–117, 2015.
[11] M. Krarti, K. Dubey, and N. Howarth, "Evaluation of building energy efficiency investment options for the Kingdom of Saudi Arabia," Energy, vol. 134, pp. 595–610, 2017.
[12] M. Krarti, M. Aldubyan, and E. Williams, "Residential building stock model for evaluating energy retrofit programs in Saudi Arabia," Energy, vol. 195, p. 11698, 2020.
[13] S. Shaahid et al., "Techno-economic potential of retrofitting diesel power systems with hybrid wind-photovoltaic-diesel systems for off-grid electrification of remote villages of Saudi Arabia," Int. J. Green Energy, vol. 7, no. 6, pp. 632–646, 2010.
[14] H. Radhi, "Evaluating the potential impact of global warming on the UAE residential buildings–A contribution to reduce CO2 emissions. Build. Environ., vol. 44, no. 12, pp. 2451–2462, 2009.
[15] S. Ben Lasoad, A. Al-Sakkaf, and S. Baharetha, "Investigation of building envelope design for hot-humid climatic conditions in Saudi Arabia," J. Scien. Eng. Res., vol. 8, no. 4, pp. 13–29, 2021.
[16] M. Roser et al., "World population growth: Our world in data," 2013.
[17] A. Gusyachkin et al., "Effects of moisture content on thermal conductivity of thermal insulation materials," IOP Conf. Ser: Mater. Sci. Eng., IOP Publishing, 2019.
[18] PIS Arabia, "The Saudi Building Code," 2018.
[19] Y. Alsaqabi et al., "Techno-environmental assessment of insulation materials in Saudi Arabia: Integrating thermal performance and LCA. Build., vol. 13, no. 2, pp. 331, 2023.
[20] M. H. Sherman and D. J. Dickerhoff, Air-tightness of US dwellings, 1998.
[21] R. Lowe et al., "Air-tightness in masonry dwellings: Laboratory and field experience," Build Serv Eng Res Technol, vol. 15, no. 3, pp. 149–155, 1994.
[22] R. Lederle, T. Shepard, and V.D.L.V. Meza, "Comparison of methods for measuring infiltration rate of pervious concrete," Constr Build Mater, vol. 244, p. 118339, 2020.
[23] B. A. Wilcox and T.A. Weston, "Measured infiltration reduction in California production houses using housewrap," Thermal Performance of the Exterior Envelopes of Buildings VIII, 2001.
[24] H. H. R. Durschlag, Air leakage of insulated concrete from houses. Massachusetts Institute of Technology. 2012.
[25] A. Elmahdy, "Quantification of air leakage effects on the condensation resistance of windows." ASHRAE Trans, vol. 109, no. 1, pp. 600–606, 2003.
[26] M. H. Sherman, Infiltration as ventilation: Weather-induced dilution. U.S. Department of Energy, Dec. 2012.
[27] D. Fugler, Air infiltration from attached garages in Canadian houses. Canada Mortgage and Housing Corporation, 2001.
[28] Y. Du et al., "A case study of air infiltration for highly airtight buildings under the typical meteorological conditions of China," Build., vol. 14, no. 6, p. 1585, 2024.
[29] Nationwide House Energy Rating Scheme (NatHERS), "Software Accreditation Protocol," Canberra, Australia: Department of Environment and Energy, 2012.
[30] M. A. Makawi, I. M. Budaiwi, and A. A. Abdou, "Characterization of envelope air leakage behavior for centrally air-conditioned single-family detached houses," Build., vol. 13, no. 3, p. 660, 2023.

[31] A. Felimban, U. Knaack, and T. Konstantinou, "Evaluating savings potentials using energy retrofitting measures for a residential building in Jeddah, KSA," Build., vol. 13, no. 7, p. 1645, 2023.
[32] B. Jones et al., "Assessing uncertainty in housing stock infiltration rates and associated heat loss: English and UK case studies," Build. Environ., vol. 92, pp. 644–656, 2015.
[33] E. Cooper et al., "Field trialling of a pulse air-tightness tester in a range of UK homes," Int. J. Vent., vol. 18, no. 1, pp. 1–18, 2019.
[34] D. B. Crawley et al., "EnergyPlus: Creating a new-generation building energy simulation program," Energy Build., vol. 33, no. 4, pp. 319–331, 2001.
[35] A. Foucquier et al., "State of the art in building modelling and energy performances prediction: A review," Renew. Sustain. Energy Rev., vol. 23, pp. 272–288, 2013.
[36] S. B. Sadineni, S. Madala, and R. F. Boehm, "Passive building energy savings: A review of building envelope components," Renew. Sustain. Energy Rev., vol. 15, no. 8, pp. 3617–3631, 2011.