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Impact of forms in balcony designs on the indoor thermal environment and energy efficiency of residential building at Dhaka

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Abstract

The designs of open and closed balconies significantly impact the thermal performance and energy efficiency of residential buildings in Dhaka City by influencing indoor temperature regulation and energy consumption. Closed balconies, with better insulation and strategic placement, enhance energy efficiency and thermal comfort compared to open balconies. This study investigates the impact of balcony design on the thermal performance and energy efficiency of residential buildings in Dhaka, Bangladesh, a tropical wet and dry climate zone. The research employs both experimental and comparative methodologies, focusing on real-time measurements of indoor air temperature and relative humidity (RH) across different balcony configurations, including open and closed balconies. The study examines the effects of balcony orientation, window-to-wall ratio, and insulation on indoor thermal comfort and energy consumption. Data were collected during both heating and non-heating days from three residential buildings: one with an open balcony and two with closed balconies. The results underscore the critical role of closed balconies in reducing temperature fluctuations and enhancing indoor comfort, acting as effective thermal buffers. Notably, south-facing closed balconies, especially those with smaller windows and improved insulation, demonstrated the greatest energy savings, reducing cooling loads by 5%–12% and up to 27% with insulation. Moreover, closed balconies with high thermal insulation were found to be more energy-efficient than open balconies, irrespective of their insulation status. These findings emphasize the importance of balcony design in optimizing thermal comfort and energy efficiency in residential buildings, particularly in tropical climates. Properly designed closed balconies, with attention to their orientation and insulation, provide significant benefits in reducing energy consumption while maintaining a comfortable indoor environment. The results offer valuable insights for improving residential building designs in Dhaka and similar climates, contributing to energy-efficient building practices that could be applied globally.

Keywords: Open Balcony, Closed Balcony; Indoor Thermal Environment; Residential Building; Energy Efficiency; Tropical Wet and Dry Climate

1. Introduction

Balconies in residential buildings play a crucial role as buffer zones, enhancing comfort, reducing energy consumption, and supporting sustainable living (Ribeiro et al., 2020; Wing Chau et al., 2004; Kennedy et al., 2015). These spaces not only contribute to energy savings but also improve indoor comfort and provide additional living space (Ribeiro et al., 2020). Research highlights that well-designed balconies can increase residents' satisfaction and overall quality of life (Wing Chau et al., 2004; Kennedy et al., 2015; Omrani et al., 2017). By 2050, Asia's energy consumption and carbon dioxide emissions are projected to increase by 1.5 times compared to 2015, underscoring the need for strategies to address energy supply constraints, climate change, and environmental impacts. Given that buildings are a major source of energy consumption, improving energy efficiency in buildings is essential for energy conservation, reducing pollution,

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and mitigating climate change (Chan, 2015). By 2019, multiple-dwelling houses accounted for 43.5% of the residential sector, with over 70% of these buildings located in large cities. Low-rise buildings (1–6 stories) accounted for 90.6% of the housing stock (Land Statistical Survey, 2019).Urban areas are experiencing growing environmental challenges, including light pollution (Falchi et al., 2016; Hu et al., 2018), noise pollution (Mueller et al., 2017), and the urban heat island effect (Nieuwenhuijsen, 2021; Sedaghat & Sharif, 2022).In this context, improving indoor thermal conditions and addressing their health impacts are critical issues (Wolkoff & Kjærgaard, 2007; Murtyas et al., 2020; Wolkoff et al., 2021). Therefore, designing energy-efficient indoor and outdoor spaces, including balconies, is vital for sustainable building practices (Chun et al., 2004).

In Dhaka, nearly every residential building now includes at least one open balcony. Currently, balconies are primarily used for practical purposes such as laundry, clothes drying, and storing garbage, with less emphasis on leisure activities like cooling off in the evening, sunbathing, or enjoying views.Studies indicate that, under optimized conditions, open balconies can decrease energy consumption for summer cooling by as much as 12.3% (Chan & Chow, 2010).This energy savings is largely due to the shading effect provided by balconies, which is considered one of the most effective solutions to prevent overheating and reduce summer energy consumption (Hastings, 2004). Most studies on open balconies have focused on warm climates, whereas in cold climates, closed balconies have been shown to reduce heating energy consumption by up to 46% (Babaee et al., 2016). While research on closed balconies exists worldwide (Voss, 2000; Wilson et al., 2000; Fernandes et al., 2015), examples of converting open balconies into closed ones have become more common since 2001 (Tomonari et al., 2003). In addition to improving energy efficiency, closed balconies provide benefits such as protection from cold, strong winds, and noise in winter, and they help maintain privacy (Tomonari et al., 2003; Lu et al., 2004; Chan, 2015). They create a cleaner, quieter, and safer environment for residents. Given the environmental challenges faced by high-density cities, such as high noise levels near busy roads, designing open balconies for residential buildings—particularly low-rise ones—may not always be the best solution and could negatively affect occupants' health. Therefore, diversifying balcony designs and improving the living environment is essential. Optimizing the building envelope design is key to creating a more comfortable and energy-efficient indoor environment for residents (Yu et al., 2008; Mitterer et al., 2012; Ascione et al., 2016).

Numerous studies highlight that passive design strategies are crucial for enhancing thermal performance and energy efficiency, especially in tropical climates like Dhaka. Research by Santamouris et al. (2021) and Wong et al. (2020) indicates that green balconies lower indoor temperatures, reduce the need for air conditioning, and can lead to energy savings of up to 30%. These passive systems provide natural shading, cutting cooling loads and electricity consumption by around 20%. Incorporating green facades can also decrease peak energy demand by 15%, improving thermal comfort and reducing energy costs by up to 25% (Li et al., 2023). Furthermore, optimizing building envelopes and managing heating setpoints (Tsp) are essential strategies for lowering energy consumption and promoting sustainability (Heidarinejad et al., 2014; Mao et al., 2017).

Moreover, optimizing building envelope design is a vital strategy for improving energy efficiency, particularly in urban environments like Dhaka, where both cooling and heating demands are significant. A well-designed envelope, which includes high-performance walls, roofs, and windows, helps minimize heat gain in the summer and heat loss in the winter, reducing the need for artificial heating and cooling. Studies have demonstrated that using advanced insulation materials, reflective surfaces, and energy-efficient glazing significantly reduces energy consumption (Zhao et al., 2021). In addition, integrating passive design elements like proper building orientation, shading devices and natural ventilation can reduce cooling loads and improve indoor comfort, thereby lowering reliance on mechanical systems (Kim et al., 2020). Li et al. (2023) further showed that optimizing the thermal properties of building envelopes can reduce energy consumption by up to 30% in tropical climates, underlining the importance of envelope design for enhancing energy efficiency.

However, thermal performance and energy efficiency in Dhaka's residential buildings are crucial for enhancing indoor comfort and reducing energy consumption, especially in the city's tropical climate. Poor indoor design, including inadequate insulation and reliance on artificial systems, drives high energy use. Passive strategies like natural ventilation, green balconies, and energy-efficient technologies such as LED lighting and double-glazed windows can improve sustainability and reduce dependency on air conditioning (Rahman et al., 2020; Ahmed & Hossain, 2019; Hossain & Rahman, 2021). Effective building design is fundamental to architectural strategies aimed at enhancing the functionality of open and closed balconies in residential buildings. Strategically designed and positioned balconies play a vital role in facilitating thermal exchange, thereby improving energy efficiency. The relationship between thermal performance and energy efficiency is significantly influenced by factors such as temperature and humidity, which are critical for maintaining a high-quality indoor environment. These considerations lead to key research questions:

- Are new buildings designed to fulfill clients' needs while neglecting optimal thermal performance for residents?

- Do residential buildings implement energy-saving strategies that enhance the thermal performance of balconies?

This research highlights the importance of well-designed balconies in improving thermal performance, energy efficiency, and indoor air quality (IAQ) in residential buildings. To investigate this, indoor thermal environment measurements were carried out in residential buildings with both open and closed balconies in Dhaka City, a region characterized by a tropical wet and dry climate. Particular focus was placed on the role of balcony spaces. The study adopts a comprehensive design model for the building envelope, incorporating factors such as balcony forms, thermal insulation performance, room orientation, and the window-to-wall ratio of the building façade. Furthermore, a comparative analysis was conducted through compliance to: The findings of this research provide valuable guidance for residential designers, offering practical strategies to enhance indoor thermal comfort and energy efficiency by optimizing residential envelope designs.

1.1 Aims and Objectives

The aim of this study is to assess how open and closed balcony designs impact thermal performance and energy efficiency in residential buildings in Dhaka, with a focus on optimizing indoor comfort and energy use. The study has three main objectives:

- To investigate and record the major climatic parameters of residential buildings with open and closed balconies in Dhaka city.
- To compare and analyze the data results, focusing on the concentration levels of thermal performance, temperature, and humidity.
- To determine the optimum configuration and placement of open and closed balconies to achieve maximum thermal performance and improve energy efficiency.

How do the designs of open and closed balconies affect the thermal performance and energy efficiency of residential buildings in Dhaka City?

2. Literature review

Table 1 Open and close balcony of energy performance 9literature based)

Source	Type of Balcony/Terrace	Methodology	Findings	Reference
Frontiers in Energy Research, 2022	Closed	Simulation and field studies on thermal buffers in cold climates	Closed balconies reduced heating loads by 8–24%, enhancing indoor thermal comfort in winter. Orientation and insulation were critical factors.	Frontiers in Energy Research, 2022
MDPI Buildings, 2024	Open	Assessment of thermal bridges in balcony connections in Mediterranean climates	Thermal bridges caused 25–40% of energy losses in open balconies. Thermally broken connections improved energy efficiency significantly.	MDPI Buildings, 2024
ResearchGate, 2020	Closed (Glazed)	Analysis of glazed balconies in vernacular buildings in Portugal	Glazed balconies captured solar gains, reduced heat loss, and improved indoor comfort.	ResearchGate, 2020
Elsevier: Energy and Buildings, 2015	Mixed (Open + Closed)	Long-term monitoring and simulation of open, semi-enclosed, and enclosed balconies	Semi-enclosed balconies balanced shading and thermal buffering, optimizing energy efficiency across diverse climate zones.	Energy and Buildings, 2015

Taylor & Francis Online, 2023	Open	Study of balcony design and surrounding construction effects on natural ventilation	Open balconies improved natural ventilation, reducing cooling energy demand in warm climates.	Taylor & Francis Online, 2023
Energy Efficiency in Architecture, 2010	Open	Building energy modeling for cooling demand in tropical climates	Open balconies reduced cooling energy consumption but required shading devices to prevent excessive solar heat gains.	Energy Efficiency in Architecture, 2010
Frontiers in Built Environment, 2023	Closed	Computational Fluid Dynamics (CFD) simulation of shading and ventilation	Life-cycle energy savings increased when passive solar gains and advanced insulation were combined.	MDPI Sustainability, 2024
Issuu Report, 2020	Open	Case studies on thermal bridging in open balcony connections	Thermal bridges in open balconies caused significant heat loss. Thermally broken connections mitigated the losses effectively.	Issuu Report, 2020

3. Methodologies

This study used an experimental-comparative approach to evaluate the indoor thermal environment of residential buildings in Dhaka, Bangladesh, which is characterized by a tropical wet and dry climate. According to climate data from the local meteorological station, Dhaka experiences hot, wet, and humid conditions, with an annual average temperature of 25°C (77°F), ranging from 18°C (64°F) in January to 29°C (84°F) in August. The monsoon season, from May to September, accounts for approximately 80% of the total annual rainfall, averaging 1,854 millimeters (73.0 inches).

The main objective of this study was to assess the impact of balcony design on the thermal performance and energy efficiency of residential buildings. The research used the Rotronic Instruments Temperature & Humidity Data Logger to record real-time measurements of indoor air temperature and relative humidity (RH). This quantitative data was complemented by qualitative observations to evaluate thermal performance, energy efficiency, and potential inefficiencies in the buildings, with a focus on structural thermal performance and energy consumption.

Measurements were taken on days chosen based on their daily average temperature and humidity. The variation in these parameters was influenced by several factors, including the use of air conditioning, heating, fans, and the opening or closing of windows.Three residential buildings in Dhaka were selected to collect data on the indoor thermal environment of buildings with balcony spaces during the summer. Among these, one building had open balconies, while the other two had closed balconies. The balconies were oriented to the south and north, respectively. Measurements were taken on both heating and non-heating days to examine how the design of the balconies affected the thermal environment in both the balcony spaces and the adjacent rooms.

Several factors were considered during the study, including the performance of the building envelope, the orientation of the balconies, the window-to-wall ratio of the balcony façades, and the design of open versus closed balconies. A total of eight different configurations were simulated based on these factors. The results were analyzed to determine the optimal configuration that would provide a comfortable indoor thermal environment while minimizing energy consumption. Table 1 presents the daily average temperature and humidity data for Dhaka during the summer of 2024. The buildings studied are located in a tropical wet and dry climate, characterized by hot summers, with average temperatures during the hottest month exceeding 0°C. Figure 1 illustrates the coldest daily average temperatures, typically occurring between May and September. The floor plans and a summary of the measurement sites are shown in Figure 1 and Table 2. Occupants typically use the rooms in the morning and evening. The open balcony is located outside the living and dining rooms on the south side, while the closed balcony is located in the bedroom, also on the south side. Each bedroom has a wall-mounted air conditioner installed. The rooms are primarily used during weekday mornings and evenings, and all day on weekends. For the closed balcony, the room temperature is controlled by central air conditioning, with air vents leading to adjacent rooms.

The open balcony, which extends from east to west outdoors, is primarily used for drying clothes. It is separated from the interior by three sliding glass windows: two between the living room and the balcony, and one connecting the south-side bedroom to the balcony. During the summer, the south bedroom's glass windows remain closed, and air conditioning is typically used to regulate the indoor temperature. The window frames around the glass are made of aluminum, which provides lower thermal insulation compared to the resin window frames used in the other buildings. The closed balcony features a sliding door with a glass window as the inner window. This space is used for drying clothes or storing idle items. The inner window remains closed throughout the winter, and dark curtains are used at night to improve insulation, ensure privacy, and regulate the temperature. Both the inner and outer window frames are made of resin, providing high thermal insulation.

In the other buildings with closed balconies, both have sliding doors with glass windows (inner windows). The closed balcony on the south side is used for laundry and drying clothes, with the inner window remaining open year-round, except when the air conditioner is in use. The closed balcony on the north side is used less frequently, primarily serving as a learning space. It features large external windows that are significantly affected by outdoor temperatures. Both the inner and outer window frames of the closed balconies are made of resin, providing high thermal insulation.

Table 2 Daily average temperature and humidity in Dhaka during the summer months 2024.

Month	Average Temperature (°C)	Average Humidity (%)
May	28.3	73%
June	28.2	78%
July	27.7	80%
August	28.2	80%
September	28.2	79%
Average	28.12°C	78%

Figure 1 Observations conducted within the building. Source: Authors, 2024.

4. Results

Table 3 Average temperature in summer 2024

Composition	Ta (°C)	Tr (°C)	Heat Load (W/m^2)	Composition	Ta (°C)	Tr (°C)	Heat Load (W/m^2)
W1-A	28.5±4.0	28.0±3.5	550	N1-A	28.5±4.0	28.0±3.5	545
W1-B	29.1±3.8	28.7±3.3	532	N1-B	29.0±3.9	28.5±3.2	537
W1-C	29.2±3.7	28.8±3.2	530	N1-C	29.1±3.8	28.6±3.1	533
W1-D	29.3±3.6	28.9±3.1	530	N1-D	29.2±3.7	28.7±3.2	531
W2-A	28.8±3.9	28.3±3.4	512	N2-A	28.8±3.9	28.2±3.3	510
W2-B	29.5±3.6	29.1±3.0	490	N2-B	29.4±3.6	29.0±3.0	495
W2-C	29.6±3.6	29.2±3.1	490	N2-C	29.5±3.6	29.1±3.1	495
W2-D	29.5±3.5	29.1±3.0	490	N2-D	29.4±3.5	28.9±3.0	493
E1-A	27.6±4.1	27.2±3.6	560	S1-A	27.6±4.0	27.1±3.5	555
E1-B	28.3±4.0	27.8±3.5	540	S1-B	28.2±3.9	27.6±3.4	545
E1-C	28.4±3.9	27.9±3.4	538	S1-C	28.3±3.9	27.8±3.5	542
E1-D	28.5±3.8	28.0±3.3	540	S1-D	28.4±3.8	27.9±3.4	545
E2-A	28.1±4.0	27.7±3.5	510	S2-A	28.2±4.0	27.7±3.5	505
E2-B	28.8±3.9	28.4±3.2	480	S2-B	28.7±3.8	28.3±3.1	485
E2-C	28.9±3.8	28.5±3.1	480	S2-C	28.8±3.8	28.4±3.1	485
E2-D	28.9±3.8	28.4±3.0	480	S2-D	28.8±3.8	28.3±3.1	485

Legend: Ta: Air temperature (mean ± standard deviation); Tr: Radiant temperature (mean ± standard deviation); Heat load: Heat load in W/m^2

This table 2 ,3 and 4 summarizes the summer average measurements for different balcony types, showing their air temperature, radiant temperature, and heat load for various orientations (W1, W2, E1, E2 for west, east, and south-facing orientations).

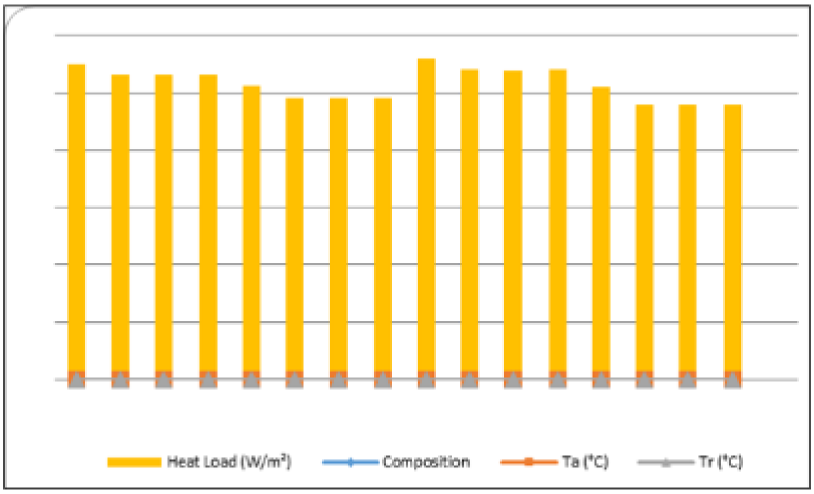
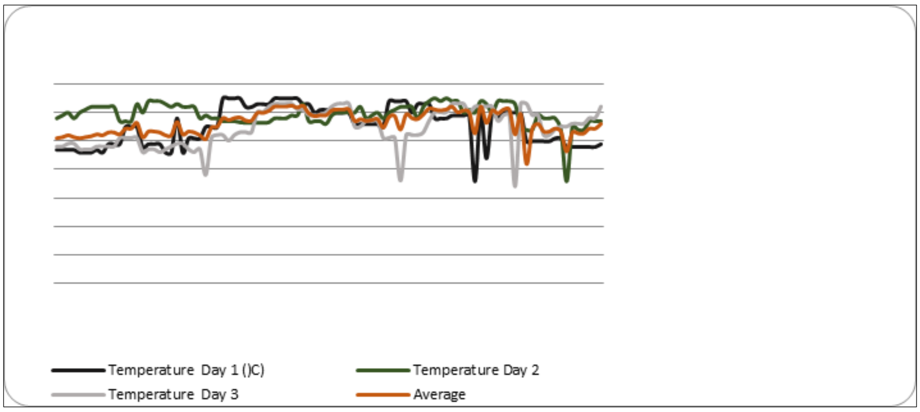


Figure 2 Average temperature in summer 2024

Table 4 Summer Temperature and Humidity Measurements

Balcony Type	Measurement Location	Ta (°C) (Mean ± Std. Dev.)	RH (%) (Mean ± Std. Dev.)
B-K	Outdoor	17.6 ± 2.9	86.8 ± 15.6
	Indoor (1.1m)	27.0 ± 3.0	73.1 ± 7.2
	Indoor (0.1m)	26.9 ± 2.2	79.3 ± 5.6
	Balcony (1.1m)	—	—
	Balcony (0.1m)	—	—
B-S	Outdoor	25.8 ± 0.9	65.8 ± 16.8
	Indoor (1.1m)	28.2 ± 1.5	81.1 ± 3.8
	Indoor (0.1m)	26.9 ± 2.1	61.7 ± 4.9
	Balcony (1.1m)	21.5 ± 3.6	65.3 ± 14.8
	Balcony (0.1m)	20.3 ± 2.4	72.6 ± 14.7
B-N1	Outdoor	24.7 ± 2.4	79.4 ± 14.5
	Indoor (1.1m)	11.2 ± 2.6	74.1 ± 11.4
	Indoor (0.1m)	20.2 ± 0.9	70.1 ± 6.4
	Balcony (1.1m)	20.8 ± 0.8	78.2 ± 11.4
	Balcony (0.1m)	29.9 ± 0.8	89.7 ± 11.0
B-N2	Outdoor	—	—
	Indoor (1.1m)	23.3 ± 3.4	68.3 ± 7.8
	Indoor (0.1m)	29.3 ± 0.7	79.4 ± 5.5
	Balcony (1.1m)	28.6 ± 1.8	79.8 ± 10.1
	Balcony (0.1m)	27.5 ± 1.4	77.3 ± 10.0



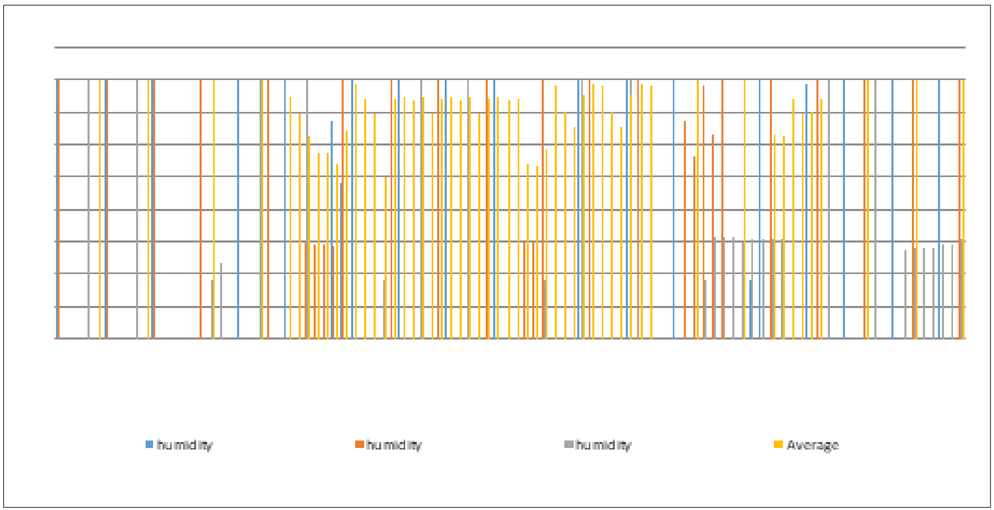


Figure 3 Summer Temperature and Humidity Measurements

4.1. Measurement of temperature variations

This study on temperature variations in residential balconies during heating and non-heating days. The findings show that the design and configuration of the balcony space—specifically whether the balcony is closed or open—play a significant role in indoor temperature fluctuations and thermal comfort.

Temperature Fluctuations on Non-Heating Days (Figure 3) The closed balcony (B-S) experienced the largest temperature fluctuations and the highest temperatures due to the "greenhouse effect," where solar heat accumulated in the closed balcony space, and the internal windows were closed. Rooms adjacent to the closed balcony exhibited small temperature fluctuations because of the heat retention from the balcony. The temperature of the closed balcony in B-N1 was more consistent with the adjacent room due to the open inner window, allowing heat transfer between the two spaces. The temperature fluctuations in rooms adjacent to open balconies (B-N2) were larger, indicating that an open balcony does not provide the same buffering effect as a closed one. Temperature Measurements on Heating Days (Figure 3B): Measurements at 0.1 meters showed minimal indoor temperature variation compared to those taken at 1.1 meters, which were affected by air blown by the air conditioner. The temperature fluctuation trends during heating days were similar to non-heating days, with the closed balcony B-S being more susceptible to solar radiation and showing dramatic fluctuations, while the adjacent room remained more stable.

This behavior supports the idea that closed balconies act as thermal buffers between indoor and outdoor environments. Daily Temperature Variation Patterns (Figure 3):In B-S (with the inner window closed), the balcony temperature was influenced by solar radiation and outdoor air temperature, but the adjacent room temperature remained stable without disturbance. In B-N1 (with the inner window open), the room temperature was higher than the balcony temperature during the night and early morning when outdoor temperatures were low. By 8:00 a.m., this situation reversed, and by 12:30 p.m., the temperatures in both spaces were equal.

The results suggest that closed balconies can transfer solar radiant heat into the room, improving warmth. Intermittent Heating in B-N2 (Figure3):When the inner window of the balcony was open, the temperature variation in the balcony space was influenced more by the indoor temperature of the adjacent rooms rather than outdoor air temperature fluctuations. The indoor temperature in the adjacent room decreased more slowly when the inner window was closed during non-heating periods (05:30–22:00 on 1 June).With the inner window open and heating on, the balcony temperature variations followed the indoor room temperature trends, indicating greater heat exchange between the balcony and adjacent room. The study indicates that closed balconies serve as effective thermal buffers, reducing indoor temperature fluctuations and improving thermal comfort. Open balconies, however, are less efficient in this regard, leading to greater temperature variability. The design and functionality of balcony spaces can significantly impact indoor environmental quality, especially in regions with extreme seasonal temperature fluctuations**.**

4.2. Effect of the balcony form on the thermal environment

The effect of balcony form on the thermal environment is analyzed by comparing indoor air temperature (Ta) and radiant temperature (Tr) during the summer period for four different balcony models. The summer average temperatures of Ta and Tr show minimal differences between closed balconies (Types B, C, and D). This suggests that the proportion of external windows to walls in the balcony has a limited effect on the indoor temperature in adjacent rooms.

Further examination of the indoor temperatures in rooms next to the balconies reveals that closed balcony types (B, C, and D) generally maintain higher indoor temperatures than open balconies. Insulated balconies, in particular, exhibit higher indoor temperatures than their non-insulated counterparts. South-facing balconies tend to have the highest indoor temperatures due to increased solar heat gain. The temperature difference between closed and open balconies is approximately 1.02°C across various orientations, with south-facing balconies providing the most significant thermal benefits. When considering temperature variations across different orientations, both general and insulated types show that east-facing rooms experience higher summer temperatures than west-facing ones, especially between 8:00 and 15:30. After this period, west-facing rooms become slightly warmer until an hour before heating begins, when temperatures tend to equalize. This is due to the differing timing of solar radiation, with east-facing rooms receiving more heat during the morning.

In results, closed balconies (Types B, C, and D) are more sensitive to orientation than open balconies, with south-facing closed balconies offering the best thermal performance. The insulation type plays a critical role in improving indoor thermal comfort, particularly during the heating period. Radiant temperature (Tr) variations align with these findings, with closed, insulated balconies exhibiting higher radiant temperatures during non-heating hours, while open, insulated balconies show higher Tr during heated nighttime.

4.3. Effect of the balcony form on heat load

The results in Table 5 and summarize the heat load simulations for four balcony types during summer. For east, west, and north orientations, the heat load differences between Types B, C, and D were minimal. However, for the south orientation, the heat load varied by 4.0%–6.3%, highlighting the influence of balcony design on heat load for south-facing units. Closed balconies with improved insulation showed significant energy savings, reducing heat loads by 11%–26% compared to open balconies. The closed balcony Type S2-C, facing south with a small window area, achieved the largest reduction of 27%. This suggests those balconies with smaller window areas and less heat loss are the most energy-efficient. Type D balconies generally had larger heat loads due to their bigger windows, which increased solar heat gain but also heat loss. However, insulated Type D balconies showed reduced heat loads compared to Type B, as solar heat gains exceeded heat transfer losses. For south-facing models, closed balconies without insulation reduced energy use by 5.2% more than insulated open balconies.

Table 5 Heat Load Reduction for Different Balcony Types (summer)

Balcony Type	Orientation	Heat Load Difference	Reduction Compared to Open Balcony	Key Observations
Type B	East, West, North	Minimal differences	N/A	Similar heat loads for non-south orientations.
	South	4.0%–6.3%	Moderate reduction	Influenced by south-facing design.
Type C	East, West, North	Minimal differences	N/A	Similar heat loads for non-south orientations.
	South	4.0%–6.3%	Moderate reduction	Smaller window area saves energy.
Type D	East, West, North	Minimal differences	N/A	Larger windows increase heat gain and loss.
	South	4.0%–6.3%	Larger reduction with insulation	Solar heat gain offsets heat transfer loss.
Type S2-C	South	Largest reduction (27%)	11%–26%	Most energy-efficient with small windows.

5. Discussion and Limitations

Proper balcony design plays a vital role in enhancing energy efficiency and sustainability in buildings. Research on open balconies has primarily focused on warm regions, where they are effective in reducing overheating during summer. For instance, studies conducted in tropical wet and dry climate zones have revealed that 55%–65% of energy consumption in some regions is allocated to cooling (Dhaka et al., 2012). However, research from Japan indicates that residents often face a higher demand for heating than cooling, with 21% of the year requiring heating and only 13% for cooling (Florides et al., 2002). This underscores the importance of examining the role of open balconies in tropical wet and dry climates, especially during summer.

This study analyzed the thermal environment and energy savings of residential buildings during summer. The findings revealed that while closed balconies can save energy and enhance comfort, they may also lead to overheating and increased energy usage in summer. To mitigate this, design features such as shading devices, air gaps, and openable windows can help balance energy consumption across seasons (Florides et al., 2002). Optimizing the building envelope, including balcony design, is key to creating a comfortable indoor environment year-round.

Numerous studies emphasize the benefits of energy-saving measures, such as insulation, in improving energy efficiency. For example, Dhaka et al. (2012) recommend using roof and wall insulation to reduce energy consumption in warm climates. Similarly, Florides et al. (2002) demonstrated that Low-E double-glazed windows could lower cooling loads by up to 24%. Furthermore, the study found that open balconies with insulation experienced slightly lower temperatures in summer compared to closed balconies. Closed balconies with smaller windows and no insulation were shown to save 4.7% more energy than open balconies with insulation, making them particularly effective during winter in tropical wet and dry climates.

This study focused on analyzing indoor temperature to assess the thermal environment of the dwelling, but indoor relative humidity was not specifically measured or analyzed. Therefore, the results of the thermal environment analysis in this paper are based only on temperature and humidity. Additionally, the study did not consider the effect of adjacent building envelopes or the shading from nearby buildings in the model's parameter settings. The findings on the effectiveness of building envelope designs with closed balconies and insulation are based on improvements in indoor thermal conditions and energy efficiency during heating periods. However, the economic benefits of these designs were not considered. The model's parameter settings and meteorological data are specific to Dhaka, Bangladesh, a tropical wet and dry climate. Differences in regulations, lifestyles, and habits in other countries may require further investigation to assess the applicability of these findings elsewhere.

6. Conclusion

The design of building envelopes, including different types of balconies and insulation, plays an important role in improving the indoor thermal environment and energy efficiency of homes in various climates. This study focused on Dhaka, Bangladesh, a city with a tropical wet and dry climate, to explore ways to optimize building envelopes for summer conditions. The main findings are:

- Field measurements showed that closed balconies act as effective thermal buffers between indoor and outdoor spaces, helping to maintain a comfortable indoor temperature. The orientation of the balcony also affects the indoor thermal conditions.
- Closed balconies are especially useful for homes in warm climates. Simulation results indicated that the cooling load of a closed balcony is lower than that of an open balcony. Closed balconies can reduce cooling loads by 5%–12%, and those with insulation can lower it by 9%–25%. Additionally, reducing the size of exterior glass windows can improve energy efficiency by enhancing insulation.
- South-facing closed balconies have a greater positive effect on indoor temperature control and energy savings compared to open balconies.
- The ratio of windows to walls in closed balconies has little impact on indoor thermal conditions in summer. The effect on cooling load is small, ranging from 3% to 5.5%, and becomes more noticeable when the balcony faces south.
- Even without insulation, closed balconies provide better thermal performance than open balconies with insulation. Therefore, designing closed balconies specifically for residential buildings in tropical climates is more energy-efficient than relying only on insulation.

This paper emphasizes the importance of designing building envelopes that are adapted to the local climate and environment. It offers valuable recommendations for designers on how to enhance thermal comfort and energy efficiency in residential buildings by incorporating well-designed balconies**.**

Compliance with ethical standards

Disclosure of conflict of interest

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