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Effect of Thermal Mass and Insulation Position in Walls on the Thermal Performance of Residential Buildings in a Cold Climate

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Highlights

- Thermal mass on the interior side and insulation on the exterior side of walls exhibit better thermal performance in cold climates.
- It reduces the HED by 4% and HDD by 3% across the different climate severities.
- The South orientation is preferred over other orientations.
- Higher WWR leads to higher energy consumption and heat loss.

Abstract

This study investigates the effect of thermal mass and insulation position on the thermal performance of residential buildings in a cold climate. A combination of numerical simulations and field measurements is employed to assess the impact of different wall configurations on heating energy demands and comfort. Configurations with thermal mass placed on the interior side of walls exhibit better thermal performance, reducing temperature fluctuations and enhancing thermal comfort. The study also explores the influence of climate severities, changing the window-to-wall ratio and building orientation on energy savings and comfort for various wall configurations. Wall B (thermal mass inside and insulation outside) reduces HED by 4% and HDD by 3% across different locations. Wall B reduced HED by 9.8% and HDD by 1.4% for a south facing building, and reduced HED by 3.2% and HDD by 2.2% for 10% WWR.

Keywords: Thermal performance, Thermal mass, Insulation, Residential buildings, Cold climate.

Introduction

As the world grapples with the escalating challenges of climate change and the urgent need for sustainable development, it becomes increasingly vital to optimize energy consumption and enhance thermal comfort in residential buildings. In India, a country with diverse climatic zones, the demand for housing is rapidly escalating due to a growing population and urbanization. The energy demand accounted for about 35% of building energy use in 2021, up from 30% in 2010 [1]. In the context of a cold climate, where low temperatures prevail for a significant portion of the year, the key factors influencing thermal performance in residential buildings are the placement of thermal mass and the implementation of proper insulation [2]. Thermal mass refers to the ability of a material to absorb, store, and release heat. Its strategic positioning within a building can help moderate indoor temperatures by absorbing excess heat during the day and releasing it when the ambient temperature drops. Additionally, insulation serves as a vital component in reducing heat transfer between indoor and outdoor environments, effectively mitigating thermal losses during cold weather.

Several studies have already demonstrated that different configurations of insulation and thermal mass have varying effects on both heating and cooling energy consumption and comfort. Kossecka and Kosny [3] carried out a whole-building energy analysis and concluded that the material configuration of the exterior wall could significantly affect annual thermal performance. The best performance was obtained when massive materials were located on the inner side. Al-Sanea and Zedan [4] showed that the insulation layer location had a significant effect on transmission loads. By placing the insulation on inside, the transmission load was reduced to 20% of that of outside insulation. Results also showed that wall orientation had a significant effect on the thermal behaviour of the building. A south-facing wall was most favoured and gave a 12% lower transmission load compared to the least favourable orientation. Changes in WWR in a low and high thermal mass building leads to lower heating and cooling demands for different climates [5]. Furthermore, there is a lack of research focusing on the performance of thermal mass in cold climates [6]. The research that does exist relating to cold climates is patchy and contradictory, and few studies look at its effects in a generalizable, quantifiable sense [6].

The primary objective of this study is to investigate the effect of thermal mass and insulation position on the thermal performance of residential buildings in a cold climate. For this purpose, a residential building is modelled, and simulations were carried out to evaluate the appropriate positioning of thermal mass and insulation required to achieve energy efficiency and improved thermal comfort. The effect of orientation, WWR, and climate severities is also evaluated for the wall configurations with respect to comfort and energy savings. The findings will guide policymakers, architects, and engineers in formulating effective building design strategies, constructing energy-efficient housing, and ultimately contributing to the sustainable development of residential infrastructure in cold climate regions of India.

Methods

A residential building was investigated through real-time field measurement. The reference building was modelled in TRNSYS software and validated using real-time field data. Simulations were carried out in the reference building model to study the variation in comfort and heating energy demand for different wall configurations. Wall configurations with the same U-value but different thermal mass were considered for simulations. The effect of the wall configurations on comfort and heating energy demand is investigated for various orientations, WWR, and climate severities.

Climate and Building Characteristics

The study pertains to Mussoorie city (30.45°N; 78.06°E), located in Uttarakhand state in India, which represents a cold climate zone (Cwb). The dry bulb temperature ranges from -4°C to 18.5°C in winter (January) and 9.8°C to 33°C in summer (May). The diurnal temperature range during winter is around 15°C, and that during summer is about 17°C. A naturally ventilated residential building was chosen to study the thermal performance through real-time field measurements. The indoor and outdoor air temperature and relative humidity are recorded at ten minutes intervals from January 2021 to December 2021 [7]. Table 1 shows the characteristics of House A.

Table 1: Characteristic description of residence.

Parameters	House A
Perimeter	41 m
Floor Area	84 m^2
Volume	235 m^3
Floor-to-floor height	2.8 m
Orientation	South facing
Wall type	230 mm Brick Masonry
Wall U-value	2.18 W/m^2K
Roof type	150 mm RCC Slab
Roof shape	Flat
Roof U-value	3.75 W/m^2K
Window type	Wooden frame with 3 mm Single clear glass
Sill height	0.8 m
Lintel height	2 m
WWR	10%
Overhang depth	0.6 m

Figure 1 shows the floor plan with the location of sensors (grey circle) and the view of House A.

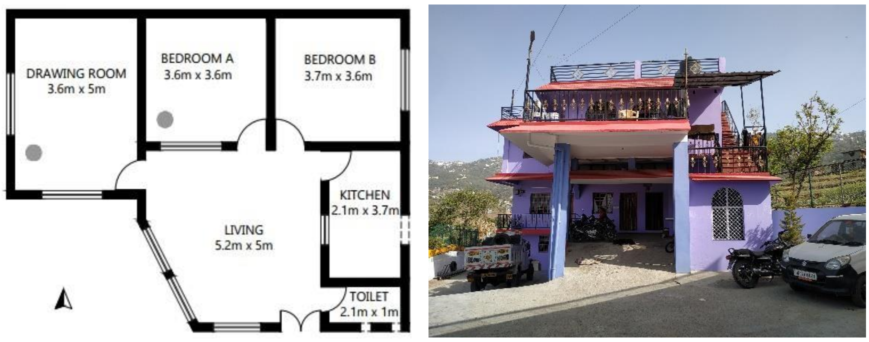


Figure 1: Floor plan showing sensor location and view of House A

Figure 2 shows the real-time indoor environment conditions in the bedroom and drawing room for four consecutive days in the winter month of January, the transition month of March, and the summer month of May. The readings are obtained using a temperature and humidity data logger with a precision of ±0.50C & ±3% RH and a resolution of 0.1 °C & 0.1% RH. The outdoor temperature ranges from -0.7°C to 31°C, and relative humidity ranges between 15% to 96% during the recorded period. The indoor temperature ranges from 3.3°C to 33.2°C, and relative humidity ranges between 20% to 95% for the measured period in House A.

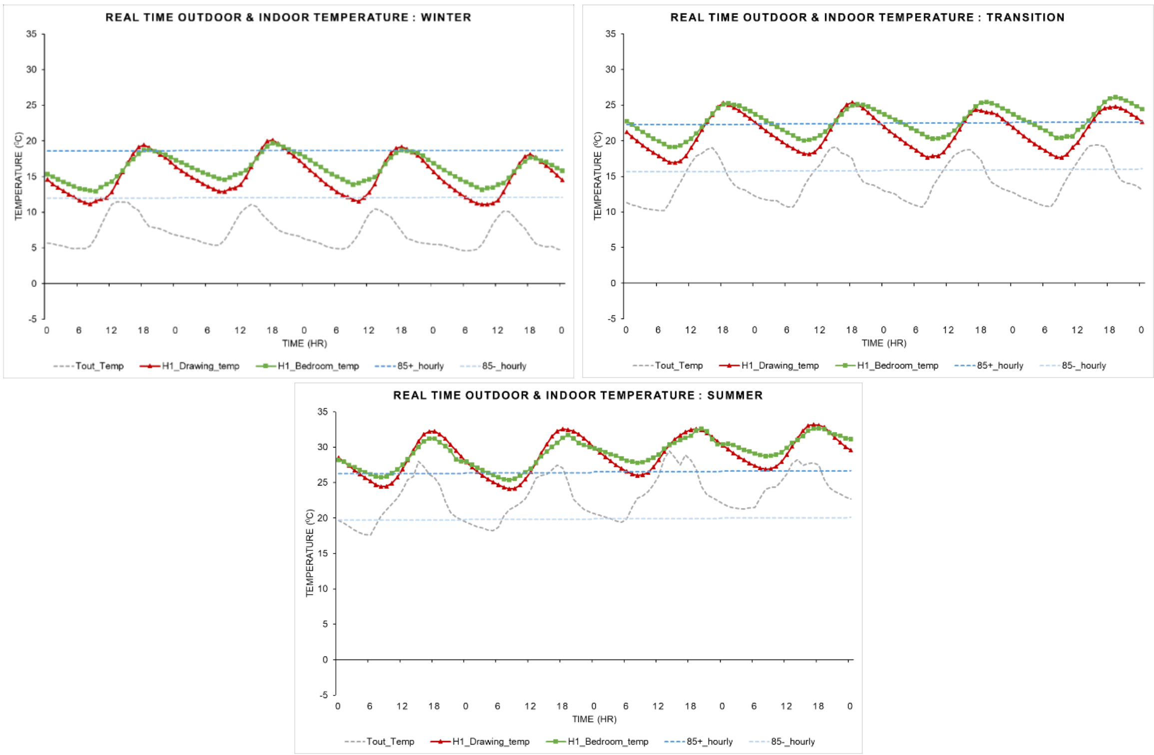
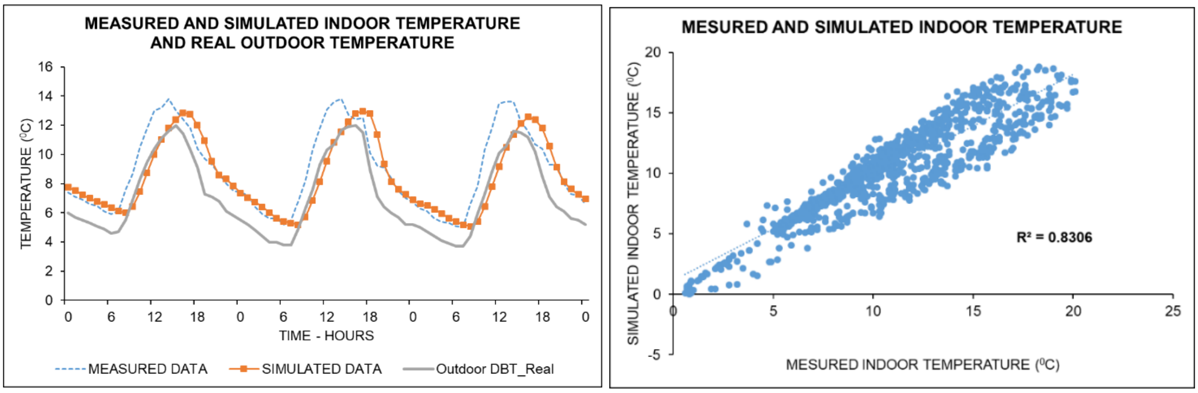


Figure 2: Indoor temperature variation measured in House A in January, March, and June

The indoor temperature of both the drawing room and bedroom remains within the IMAC (Indian Model for Adaptive Comfort) comfort band of 85% acceptability limits [8] in winter. But remains hotter during the transition and summer months. This may be due to the South-West orientation of the drawing room and the absence of external walls and windows in the bedroom. The external windows on the south and east of the drawing room remain open from 8 am to 5 pm in summer and transition months, while in winter, the windows remain open from 10 am to 3 pm. The internal window of the bedroom remains closed throughout the year.



(a) (b)

Figure 3: (a) Validation of measured and simulated indoor temperature data for three consecutive days. (b) Scatter plot showing R^2 value of the measured and simulated data for the measured period

Validation

House A was modelled in TRNSYS, and the simulation results were validated with the actual field measurements under similar conditions comparing the indoor air temperature. The results of a survey on the average and maximum errors recorded in simulation validation studies are presented, whereby the typical maximum error is below 7°C, and the average error is 4.3°C. The CVRMSE (Coefficient of Variance of the Root Mean Square Error) value between modelled and measured indoor air temperature is 9.4%. According to the ASHRAE Guide [9], the models are validated when the CVRMSE values fall within 30%, and the R^2 value is > 0.75 for hourly data. CVRMSE is given by Equation (1):

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{Ni}\frac{(Mi-Si)^2}{Ni}}}{\frac{1}{Ni}\sum_{i=1}^{Ni}Mi} \qquad (1)$$

where Mi – Measured data; Si – simulated data; Ni – count of the number of the data used in the validation. Figure 3 (a) shows the simulated and measured indoor temperature data for three consecutive days in House A. There was a delay in peaks of measured and simulated data due to infiltration. This validated model is used to carry out further simulations. Figure 3 (b) shows the R^2 value of the simulated and measured temperature for the measured period.

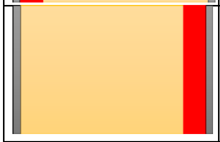
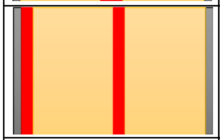
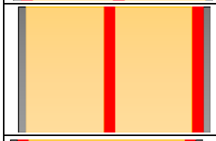
Wall Configuration

Wall assemblies were created to carry out simulations to compare heating energy demand and comfort. Wall assemblies with the same U-value were considered, while they differ with regard to location and number of insulation layers. One, two, and three insulation layers are investigated. The thermal mass comprises either one 300-mm-thick Random rubble masonry or two 150-mm-thick random rubble masonry, as it is practically applicable and locally available material in Uttarakhand [10]. A 10-mm-thick cement plaster on each side encloses the wall assembly. The properties of materials are summarized in Table 2, while Table 3 gives the schematics, U-value, and internal areal heat capacities [11] of wall configurations. The internal areal heat capacity describes the real capacity to accumulate heat on the inner side of a building element. Since the main idea was to investigate the effect of varied thermal mass, the U-values have been kept the same in all the cases, and hence, the conventional brick wall with cement plaster is not included, as its U-value will change with respect to other wall assemblies.

Table 2: Material Properties [12]

Material	Density (kg/m^3)	Conductivity (W/mK)	Specific heat capacity (J/kg K)
Random rubble	1922	1.585	880
Cement plaster	1762	0.721	840
Insulation_EPS	30	0.032	1250

Table 3: Wall configurations with differing locations of insulation and thermal mass [13]

Schematics	Wall	Assembly (Inside to outside)	U-value (W/m^2K)	Internal Areal heat capacity (kJ/m^2K)
	Wall A	10 mm thick cement plaster + 30 mm thick EPS insulation + 300 mm thick random rubble masonry + 10 mm thick cement plaster	0.75	20.6
	Wall B	10 mm thick cement plaster + 300 mm thick random rubble masonry + 30 mm thick EPS insulation + 10 mm thick cement plaster	0.75	72
	Wall C	10 mm thick cement plaster + 150 mm thick random rubble masonry + 30 mm thick EPS insulation + 150 mm thick random rubble masonry + 10 mm thick cement plaster	0.75	77.5
	Wall D	10 mm thick cement plaster + 15 mm thick EPS insulation + 150 mm thick random rubble masonry + 15 mm thick EPS insulation + 150 mm thick random rubble masonry + 10 mm thick cement plaster	0.75	26
	Wall E	10 mm thick cement plaster + 150 mm thick random rubble masonry + 15 mm thick EPS insulation + 150 mm thick random rubble masonry + 15 mm thick EPS insulation + 10 mm thick cement plaster	0.75	75.4
	Wall F	10 mm thick cement plaster + 15 mm thick EPS insulation + 300 mm thick random rubble masonry + 15 mm thick EPS insulation + 10 mm thick cement plaster	0.75	25.4

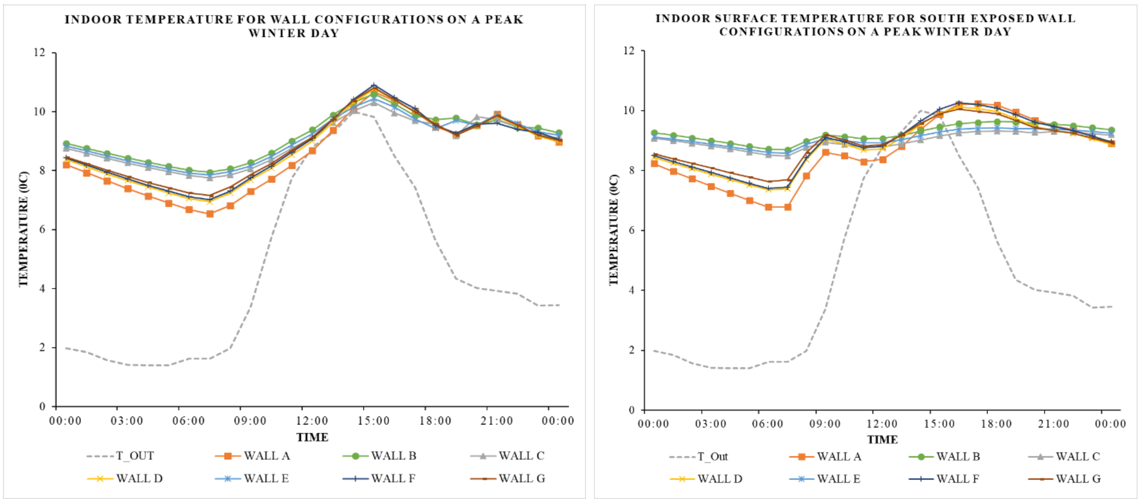
	Wall G	10 mm thick cement plaster + 10 mm thick EPS insulation + 150 mm thick random rubble masonry + 10 mm thick EPS insulation + 150 mm thick random rubble masonry + 10 mm thick EPS insulation + 10 mm thick cement plaster	0.75	31.4
Grey: Cement plaster; Red: Insulation; Yellow: Random Rubble masonry				

The wall configurations were compared to investigate the heating energy savings and reductions in HDD (Heating Degree Days) with respect to climate severities, orientation, and WWR. The Heating Degree Days are calculated in accordance with the EN 15251 standard [14], which provides a comprehensive method for determining the HDD values based on the outdoor temperature. The study includes three locations with varying climate severity levels: MILD: New Tehri (HDD = 2983), COLD: Mussoorie (HDD = 3237), and COLDER: Chakrata (HDD = 3491). The window-to-wall ratio (WWR) ranges from 10% to 40%, and all four orientations (North, South, East, and West) are simulated to evaluate the impact of wall configurations on the thermal performance of the residence. The drawing room facing south west was selected for running simulations on the validated model of House A for assessing the heating energy demand and heating degree discomfort hours.

Results

The paper investigated the effect of thermal mass and insulation position on the thermal performance of residential buildings in a cold climate. Simulations were performed for seven different wall configurations to assess the heating energy demand and comfort. The drawing room was simulated under two conditions: First – naturally ventilated condition, where the windows were programmed to open when the indoor temperature exceeded 24°C and close when the outdoor temperature surpassed the indoor temperature. Secondly – heating conditions, where a heating set point of 22°C is set as per EN 15251 standard to heat the room and maintain a comfortable temperature inside. This provides insight into the thermal behaviour of the room and heating energy requirements for different wall configurations.

Figure 4 a) shows the fluctuations in indoor temperature conditions for different wall configurations on a peak winter day (December 21).



(a) (b)

Figure 4: (a) Indoor air temperature and (b) surface temperature conditions for different wall configurations on a peak winter day

The outdoor temperature ranges from 1.4°C to 10°C on a peak winter day (December 21) considered here. Analysis of indoor temperature reveals that Wall A exhibits an ambient temperature that is 1.4°C lower than Wall B at 7 am when the indoor temperature is lowest. Despite having the same U-value, the variation in the positioning of thermal mass and insulation causes differences in indoor temperature conditions. Based on the decreasing order of preference in terms of indoor temperature, the ranking of walls would be Wall B, Wall E, Wall C, Wall G, Wall F, Wall D, and Wall A. Figure 4 b) shows the indoor surface temperature for a south exposed wall for different wall configurations. The exterior surface temperature of the walls varies between 3.3°C and 9.6°C. The indoor surface temperature for Wall A is 1.8°C lower than Wall B. The ΔT for Wall A is 1.6°C whereas ΔT for Wall B is 1°C only on a peak winter day. This suggests there is less fluctuation in the indoor surface temperature for Wall B than for Wall A. The outdoor temperature ranges from 18°C to 32°C on a peak summer day (June 21). Analysis of indoor air temperature and surface temperature reveals that at 6 pm, when the indoor temperature reaches its peak, Wall A maintains an ambient temperature of 0.1°C cooler than Wall B, while its surface temperature is 0.2°C warmer than Wall B. Since there is no significant difference in indoor air temperature and surface temperature, Wall B remains the preferable choice over Wall A, even during the summer months.

To evaluate the thermal performance of the buildings, various thermal performance indexes like time lag, damping, and decrement factor are used [15]. Table 4 presents the maximum and minimum thermal performance of different wall configurations in terms of decrement factor for surface temperature, damping, and time lag based on indoor and outdoor air temperature for a typical winter month (Dec+Jan).

Table 4: Thermal performance of different Wall configurations in winter month

Wall	Decrement factor		Damping (%)		Time lag (hrs)	
	min	max	min	max	min	max
Wall A	0.3	0.7	40	62	1	4
Wall B	0.1	0.5	42	89	1	5
Wall C	0.1	0.7	23	90	1	5
Wall D	0.3	0.7	22	69	1	3
Wall E	0.1	0.7	31	90	1	5
Wall F	0.3	0.8	21	68	1	3
Wall G	0.2	0.9	10	72	1	3

From Table 4, it is evident that Wall B exhibits the lowest decrement factor, highest damping, and highest time lag among the different wall configurations. This indicates that Wall B outperforms the other configurations in terms of thermal performance. Figure 5 shows the heating energy demand for a peak winter day with different wall configurations.

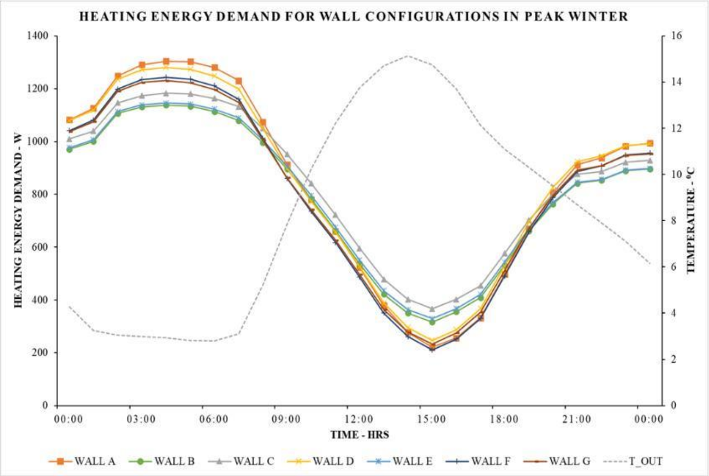


Figure 5: Heating energy demand for different wall configurations on a peak winter day

Analysis of heating energy demand for a peak winter day shows that HED for Wall A is 150 Watts or 12% higher than Wall B. Therefore, Wall A serves as the reference case for comparing the energy savings and reduction in heating degree days among other wall configurations.

Effect of Wall Configuration on climate severity wise thermal performance

The study examined the variations in indoor air temperature and heating energy demand across different climate severities represented by the selected locations, i.e., New Tehri, Mussoorie, and Chakrata. The locations were selected to represent the mild, cold, and colder conditions. The results are for the drawing room with external walls facing south and west. The results demonstrated that buildings located in harsher climates experienced higher heating energy demand and more significant temperature fluctuations. Table 5 shows the reduction in HED and HDD for different wall configurations and climate severities.

Table 5: Effect of wall configurations on climate severities showing reductions in HED and HDD

Wall	New Tehri		Mussoorie		Chakrata	
	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction
Wall A	1642 kWh	2035 hrs	1720 kWh	2150 hrs	2211 kWh	2210 hrs
Wall B	**-4.2**	**-3.1**	**-3.2**	**-2.2**	**-2.8**	**-0.5**
Wall C	-4	-2.3	-3	-1.7	-2.6	-0.4
Wall D	-1.7	-0.6	-1.3	-0.6	-1.1	-0.2
Wall E	-4	-2.7	-2.8	-2.1	-2.6	-0.4
Wall F	-1.7	-1	-1.2	-0.6	-1	-0.1
Wall G	-2.3	-1.2	-1.7	-0.9	-1.4	-0.2

There is an increase of 25% in HED with the increase in climate severity from New Tehri to Chakrata. Among the various wall configurations, Wall B demonstrated a reduction in Heating Energy Demand (HED) ranging from 3% to 4% and a reduction in HDD ranging from 0.5% to 3% across the different locations.

Effect of Wall Configuration on orientation wise thermal performance

The impact of different building orientations on indoor air temperature and heating energy demand was analyzed. The results are for the drawing room in Mussoorie. The results indicated that buildings with favorable orientations, such as south-facing walls, experienced better thermal performance. These orientations allowed for increased solar gain, resulting in reduced heating energy demand and improved thermal comfort. Table 6 shows the reduction in HED and HDD for different wall configurations and orientations.

Table 6: Effect of wall configurations on orientation showing reductions in HED and HDD

Wall	North		East		West		South	
	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction
Wall A	1720 kWh	2150 hrs	1591 kWh	2119 hrs	1304 kWh	2045 hrs	1297 kWh	1989 hrs
Wall B	**-3.2**	**-2.2**	**-3.9**	**-1.8**	**-7**	**-1.7**	**-9.8**	**-1.4**
Wall C	-3	-1.7	-3.2	-1.3	-5	-1.1	-7.3	-1
Wall D	-1.3	-0.6	-1.4	-0.5	-2.7	-0.4	-3.5	-0.4
Wall E	-2.8	-2.1	-2.9	-1.4	-5.6	-1.3	-8.3	-1.2
Wall F	-1.2	-0.6	-1.4	-0.5	-1.8	-0.5	-1.9	-0.4
Wall G	-1.7	-0.9	-2	-0.8	-2.7	-0.7	-3.2	-0.6

As the orientation of the building changes from north to south, the HED is reduced by 24%, and the HDD is reduced by 8%. Among the various wall configurations, Wall B demonstrated a reduction in Heating Energy Demand (HED) of 9.8% and a reduction in HDD of 1.4%, specifically for the south orientation. These reductions in HED and HDD indicate that Wall B outperformed all other wall configurations, demonstrating the highest energy efficiency and improved thermal performance for all orientations.

Effect of Wall Configuration on window-to-wall ratio wise thermal performance

In a cold climate, the increase in Window-to-Wall Ratio (WWR) can have a notable impact on building heating energy demand. As the WWR increases, the surface area of windows also increases, leading to higher heat loss from the building envelope. This increased heat loss through windows can result in higher heating energy demand to maintain desired indoor temperatures. Simulations were carried out to study the effect of wall configurations on increasing WWR. The simulations are for the drawing room facing south and west in Mussoorie with a 3 mm single clear glass window with a U-value of 5.6 W/m^{2}K. Table 7 indicates the reduction in HED and HDD for different wall configurations and WWR.

Table 7: Effect of wall configurations on WWR showing reductions in HED and HDD

Wall	WWR 10 %		WWR 20 %		WWR 30 %		WWR 40 %	
	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction
Wall A	1720 kWh	2150 hrs	1762 kWh	2162 hrs	1795 kWh	2188 hrs	1886 kWh	2252 hrs
Wall B	**-3.2**	**-2.2**	**-2.5**	**-1.7**	**-2**	**-1.6**	**-1.8**	**-1.3**
Wall C	-3	-1.7	-2.2	-1.3	-1.9	-1.2	-1.7	-1.1
Wall D	-1.3	-0.6	-1.1	-0.2	-1	-0.2	-0.8	-0.1
Wall E	-2.8	-2.1	-2.5	-1.3	-1.7	-1.2	-1.5	-1.1
Wall F	-1.2	-0.6	-1	-0.2	-1	-0.2	-1.3	-0.2
Wall G	-1.7	-0.9	-1.5	-0.4	-1.3	-0.3	-0.9	-0.3

It was observed that as the WWR increased, the HED increased by 8.8% from WWR 10% to WWR 40%, and the HDD increased by 4.5%. This indicates that in cold climates, lower WWR is preferred. Among the various wall configurations studied, Wall B consistently demonstrated a reduction in Heating Energy Demand (HED) and Heating Degree Days (HDD). For a 10% WWR, Wall B exhibited a decrease in HED by 3.2% and HDD by 2.2%. This trend persisted as the WWR increased from 10% to 40%. However, higher WWR with double glazed windows and brick masonry walls will lead to lower heating energy demand [16], which is opposite to the case discussed here.

Conclusion

In conclusion, this study investigated the effect of thermal mass and insulation position on the thermal performance of residential buildings in a cold climate. The research aimed to understand the impact of these factors on energy consumption and thermal comfort conditions in residential buildings. The results of the study demonstrated that the positioning of thermal mass and insulation significantly influenced the thermal performance of residential buildings. By varying the wall configurations, it was observed that different combinations of thermal mass position and insulation had varying effects on both heating demands as well as indoor thermal comfort. The findings indicated that the location of thermal mass played a critical role in regulating indoor temperatures. Configurations with thermal mass placed on the interior side of the walls exhibited better thermal performance by reducing temperature fluctuations and enhancing thermal comfort. In contrast, configurations with thermal mass placed on the exterior side resulted in higher temperature variations and increased energy consumption.

Furthermore, the study explored the impact of climate severities, orientations, and window-to-wall ratio on energy savings and comfort. The study revealed that harsher climates resulted in increased heating energy demand, while changing the orientation from north to south decreased heating energy demand, and increasing the window-to-wall ratio led to higher heat loss and increased heating energy demand. Among the various wall configurations analyzed, Wall B, with thermal mass positioned on the interior side and insulation on the exterior side, consistently exhibited superior performance in terms of energy demand reduction and thermal comfort across all conditions of climate severities, orientation and WWR. The thermal mass layer inside delays the heat loss and maintains the indoor air temperature while the thick insulation layer outside resists the heat loss to outside.

Nonetheless, practical challenges arise when applying insulation on the outer side of the wall rather than the inner side. Additional protective measures must be taken externally to shield the insulation from potential harm caused by sun and rain exposure. Consequently, there is a 10% escalation in costs due to the need for separate scaffolding installation.

Overall, this research highlights the significance of thermal mass and insulation positioning in optimizing the thermal performance of residential buildings in cold climates. The findings of this study contribute valuable insights for architects, engineers, and policymakers in designing energy-efficient residential buildings in cold climate regions. By considering the optimal positioning of thermal mass and insulation, it is possible to create buildings that provide comfortable living conditions while minimizing energy consumption and promoting sustainability in the built environment.

In future research, there is potential for exploring additional thermal mass materials such as dense concrete, heavy-weight hollow concrete blocks, brick, and cavity walls. These materials play a crucial role in the thermal properties of the building envelope, affecting the temperature difference between the indoor and outdoor environments and consequently impacting energy efficiency. Furthermore, conducting a sensitivity analysis on the key thermophysical properties of construction materials with respect to climate severities could be an area of focus for future studies.

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