J Ther Eng, Vol. 10, No. 5, pp. 1198–1211, September, 2024

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000861

Research Article

Optimum insulation thickness for external building walls for different climate zone in India

Mohd SHAHID[1,*], Munawar Nawab KARIMI[2], Atul Kumar MISHRA[1]

[1]*Department of Mechanical Engineering , Satya College of Engineering and Technology, Palwal, Haryana, 121105, India*
[2]*Department of Mechanical Engineering, Jamia Millia Islamia, New Delhi, 110025, India*

ARTICLE INFO

Article history
Received: 05 October 2021
Revised: 14 February 2022
Accepted: 21 February 2022

Keywords:
Annual Cooling Cost; Base Temperature; Cooling Degree Days; Energy-Saving; Optimum Insulation Thickness

ABSTRACT

The current study used degree-day method to determine the optimum insulation thickness for different insulation materials. Some of the commonly used insulation materials available in the market are considered in the study. Materials used in the study are, fiberglass rigid, urethane rigid, fiberglass urethane, perlite, and extruded polystyrene. The cooling degree days were calculated using the base temperature varies from 18°C to 26°C for the four major cities like Mumbai, New Delhi, Kolkata, and Chennai of India. The study aims to analyze the effect of the number of cooling degree days and base temperature on insulation thickness and also determine the variation of annual cooling cost with the insulation thickness. The result shows that the optimum insulation thickness varies with the cooling degree days and is also influenced by the electricity rate and the cost of insulation material. Based on the result, it is found that optimum insulation thickness is affected by the thermal conductivity of the material, base temperature, CDD, material cost, and fuel cost. The result shows best suitable insulation materials for Delhi, Mumbai, Kolkata, and Chennai are urethane rigid, fiberglass urethane, urethane rigid, and fiberglass rigid respectively. The optimum insulation thicknesses vary between 1 and 12 cm for the different base temperatures and cities. Annual cooling cost per m^2 is calculated for the base temperature 21 °C and 24 °C, and the result shows that fiberglass urethane has the lowest annual cooling cost for different cities. Energy-saving varies with the thickness of the insulating materials apply on the wall. In addition with the help of insulation, energy can be saved up to 80% and achieve energy-efficient buildings.

Cite this article as: Shahid M, Karimi MN, Mishra AK. Optimum insulation thickness for external building walls for different climate zone in India. J Ther Eng 2024;10(5):1198–1211.

INTRODUCTION

Industrial development, the rapid growth in the world population, and the continuous increase of various global social welfare have led to a surge in the demand for energy all over the world in recent years. In this regard, Building Sector consumes the largest energy across other sectors. In the world, the building sector consumes 36% of total energy use and 40% of the total CO_2 emission [1] (Global report 2018 UN). There are many tools to reduce energy

***Corresponding author.**
*E-mail address: mohammadshahidmech@gmail.com

This paper was recommended for publication in revised form by Associate Editor Tolga Taner

consumption through the building like optimization of building parameters [2]. Apart from these techniques, a very simple way to reduce energy consumption is by using insulation. Insulation techniques are used for the last so many years to reduce heat transfer from the buildings. In the complex structure, optimization techniques become more complex, and the equation complexity increases and to solve them software is required. A complicated structure can be defined as one that has complex geometries or one that requires sophisticated structural analysis methods and theories (such as multi-physics modeling, coupled FEM and SPH modeling analysis, and nonlinear geometrical analysis). Furthermore, due to the complexity of their structural type, big-scale complex structures, such as the large station complex in Kyoto Train Station, large-scale stadiums, and airport terminals, can be classified as complex structures. Insulation is still an important and major tool for the external wall of buildings which improves building energy performance. The quality of insulating materials depends on their flexibility, adaptability, and workability to the regional, national, and even local buildings. In literature generally, the degree hour or degree days method is used to evaluate the cooling and heating loads of the buildings because the method is easy and quite simple [3, 4]. In [5] a review of the literature was conducted to determine the appropriate thickness of thermal insulation material and its impact on energy consumption in a building envelope. The idea of thermal insulation is that adequate insulation installation using energy-efficient materials reduces heat loss or gain, resulting in lower energy costs [6].

Thermal insulation properties and performance of insulation materials can be improved by investigating their transient thermal behaviour [7, 8]. There are several theoretical and experimental studies on transient thermal behavior and flow characteristics in pipes surrounded by insulations in buildings. In [9-11] investigate the characteristics of pressure drop and methods of improvement of heat transfer in 3D and twisted tape geometrical pipes, analysis of flow field and thermal performance [12-14], pressure drop characteristic [15-17], and heat transfer enhancement in 3D pipes [14, 18-20].

As the influence of climate change grows daily, its impacts are seen on all humans. Irregular variations in climate conditions, whether measured in heating or cooling degree days, impact the environment [21-22]. Saint Akadiri et al. [23] considers the cooling degree days, heating degree days, ecological footprint, for analysis of their effects on Environment Degradation. Cooling and heating degree day may affect by the location of the building. Climate change affects the number of degree days requirement for cooling and heating in a building. Spinoni et al. [24] investigate the cooling degree day and heating degree day for the different locations in Europe. Temperature variation in the outdoor environment directly affects energy utilization for the heating and cooling in the buildings [25], as many works have outlined [26, 27] building's energy consumption is affected by the change in the environment temperature. For example [28, 29] the effect of climate changes and energy demand was investigated by degree days method on the Swiss building and the effect of change in climate on the energy performance of building for the city Rome, they found that heating conduction reduced up to 21% and 18% in residential and office building respectively.

Ramon et al. [30] analyzed the heating and cooling degree day for the different periods, they found a 27 % decrease in HDD for the period of 1976- 2004 and 2070-2098. From the above literature, it has been found that changes in degree days because of the climate conditions, therefore in this paper degree days have been evaluated for the different weather of India. Energy demand for buildings varies with the climate and hence required optimal insulation for saving energy. The base temperature is the main parameter for the calculation of degree days, with the help of degree days cooling and heating energy requirement in the building has been evaluated. D'Amico et al. [31] demonstrates the application of the degree-day method for the calculation of the heating, ventilation, and air condition load of the building and identifies the relationship between heating energy performance and heating degree day. Variation in the degree days changes the heating and cooling energy requirement in the building, therefore for the specific degree days an optimum thickness of insulation materials is required to save heat loss from the external wall of the building. Therefore in this paper, for the different degree days, optimum insulation thickness has been evaluated,

In many works of literature, different characteristics of building insulation are studied. For example, Mohsen and Akash [32] works on energy-saving measured for different insulation materials like wool, rock, and polystyrene with air gap and they found 77% energy saving by polystyrene material. They apply polystyrene material on the wall and roof. Jaber [33] found that by using the viable insulation material to ceiling and wall, heating load for space could be reduced up to 50%. Al-Sallal [34] compared the two insulation materials fiberglass and polystyrene for cold and warm climates. They investigate the payback period in their study and found that the payback period is shorter in a warm climate as compared to a cold climate. Comakli and Yuksel [35] determine the optimum insulation thickness for the coldest cities in Türkiye. They found that energy saving up to 12.13 $/m^2 for the building wall over a lifetime of ten years. Bolatturk [36] determines the optimum insulation thickness for the different zones of Türkiye by considering various fuels like LPG, fuel oil, coal, and natural gas. Bademlioglu et al. [37] determine the optimum insulation thickness for the vertical wall of the building facing different orientations by considering the solar radiation. They calculated the optimum insulation thickness on a vertical wall facing north, east, west, and south is 5.11, 6.68, 4.95, and 4.65 cm respectively. Cay and Gurel [38] determine the optimum insulation thickness using the payback, and energy saving for the different climate regions in four cities of Türkiye. Kurekci [39] determine the optimum insulation thickness reimbursement period using the cooling and heating degree day method and also investigate life cycle cost analysis for 81 territories of Türkiye by considering four distinct fuels and five distinct insulation material. Dombayci [40] determine the optimum insulation thickness by considering two different insulation material for territories located in four different climate zone of Türkiye (Table 1).

The energy demand in India is continuously increasing, and growing at an average of 3.6 percent per year over the last 30 years due to exponential population increase and improved living standards [41]. India is the world's sixth-largest energy consumer, accounting for 3.4 percent of worldwide energy consumption. Industrial, building (residential/commercial), transportation, and agriculture account for the majority of total energy usage. The construction sector consumes approximately 30% of total energy consumption and is growing at an annual rate of 8% [42]. Space heating and space cooling in the building consumes the most energy of all utilities, and it continues to rise as living standards rise and information technology advances at an exponential rate. The energy usage for space heating-cooling and the heat transfer rate is reduced when the building envelope is properly insulated.

Insulation materials are chosen depending on their heat conductivity and cost. An increase in the insulation thickness will reduce the amount of energy required for space heating and cooling, but the installation cost and cost of insulation increases, necessitating an optimum thickness to minimize the investment cost. Over the life of the building, there should be an optimal insulation thickness that decreases the energy cost of space heating–cooling and investment cost. For many years, people have been using insulating materials to minimize heat transmission in buildings. The growing need for space heating and cooling, as well as energy conservation concerns and rigorous environmental regulations, has prompted a reconsideration of the problem of thermal insulation. Even though India's energy usage is substantially lower than the global average, Indian buildings waste a large amount of energy due to a lack of energy-efficient methods. Commercial and residential establishments with installed air-conditioning systems in almost all of the country's six climatic zones lack the use of energy-efficient equipment and basic practices such as wall insulation, roof insulation due to a lack of awareness of energy conservation needs and poor purchasing capacity.

It is found from the literature review that majority of the research articles considered the case of cold countries like Türkiye and Italy, and only a few research scholars have addressed the case of region with mixed climatic condition, like India.Indian Climate is different from the other country which is divided into various climate zones. In the earlier work, optimum insulation thickness is found to be

Table 1. The summary results of the previous studies related to thermal insulation thickness

Paper	Method	City/Place	Optimum thickness	Insulation material
Bolatturk [36]	LCC	Four cities in Türkiye (totally 16 cities)	Thickness varies from 0.019 to 0.172 m depending on cities and fuel types.	Polystyrene
Comakli and Yuksel [35]	LCC	Türkiye (Erzurum, Kars, Erzincan)	Thickness obtained 0.085 m, 0.105 m, 0.107 m	Styrofoam
Dombayci et al. [40]	LCC	Denizli/Türkiy	0.032-0.138 m for rock Wool. 0.076-0.259 m for EPS.	rock wool, Expanded polystyrene
Kaynakli [6]	-	Türkiye (Bursa)	Thickness varies between 0.053 and 0.124 m depending on fuel types	rock wool (for basement) Polystyrene (for external walls), fiberglass (for ceiling)
Bademlioglu et al. [37]	LCC	Türkiye	0.0689 m and 0.0558 m	extruded polystyrene (XPS)
Cay and Gurel [38]	LCC	Türkiye	thicknesses varies between 0.045 and 0.195 m	extruded polystyrene
Shanmuga Sundaram [44]	LCC	India	0.232–0.108m in Trichy 0.226–0.105m in Chennai, 0.216–0.100m in Hyderabad, 0.204–0.094m in Trivandrum, and 0.244–0.114m in Kurnool	Foamed PVC Foamed polyurethane Expanded polystyrene

varying between 2 cm to 14 cm for the cold climate like Türkiye and Italy for the different insulation materials. For the case of India, energy saving was calculated for the different base temperatures [43] and did not focus on insulation thickness and in [43] optimum insulation thickness is calculated only for polystyrene and polyurethane insulation material for the five cities of South India. As comparing the study with [43] and [44], this study is an effective analysis of cooling degree day and base temperature on insulation thickness and annual cooling cost whereas [43] and [44] look into the problem of energy saving for different base temperatures and finding optimal thickness of the insulating material (polystyrene, polyurethane) for the external wall of the building. . To the best of the knowledge of the authors the existing literature lacks the analysis at different base temperature, and this forms the motivation for the current study. The present work specifically takes into account the cases of four major cities, namely Mumbai, Chennai, Kolkata, and New Delhi, having different climates.

The present study undertakes four different cities of India, namely Mumbai, Kolkata, New Delhi, and Chennai. Optimum insulation thickness was calculated using the cooling degree method; firstly degree day was determined for the four cities of India. The cooling degree day was calculated for different base temperatures that vary from 18 degrees Celsius to 26 degrees Celsius. The insulation thickness was calculated for five different insulation materials. i.e, extruded polystyrene, urethane rigid, fiberglass rigid, perlite, fiberglass urethane. The study aims to analyze the effect of cooling degree day's value and base temperature on optimum insulation thickness and find the relationship between base temperature and cooling degree days. The study also investigates the effect of insulation thickness on the annual cooling cost required for the building.

The main objective of the work is to analyze the impact of CDD and base temperature on the insulation thickness in different climate conditions and secondly to evaluate the optimum insulation thickness for different climate zones by considering the factors like electricity rate, cop, material cost, thermal conductivity, solid burnt clay brick wall, insulation cost, etc. further, the study is also aimed at identifying the best material and its thickness for suitable the different climate zones of India, followed by identifying the best insulation material according to the annual cooling cost and its corresponding base temperature.

METROLOGICAL DATA

India (20.5937° N, 78.9629° E) is a vast country having different types of climate in its different parts. These differences in the climate are because of the location of India. India is located near the equator therefore India comes in warmth country. And the temperature in summer is very high. India has four types of climatic regions, tropical wet, tropical dry, subtropical humid climate, and mountain climate. There are three seasons in India winter summer and rainy season. The average temperature in winter is about 10-15 degree Celsius and in summer is 30-35 °C and sometimes more than 40 °C due to heat waves from Africa. Delhi is the capital of India located at Latitude 28.7041 and Longitude 77.1025. The summer season of Delhi is very hot, temperatures rise to 45°C, and the average temperature in the summer is about 35-40°C. The relative humidity is about 45% in May and the average temperature is 33°C. The average temperature in June is 34°C and relative humidity is 55% (Table 2).

Methodology

Degree days are now an important climatic parameter used in the calculation of heating load and cooling load from the building. The degree days are the sum of the temperature differences between base temperature and average outdoor temperature. The base temperature is considered as the reference temperature on which degree days are calculated. The heating system will provide the heat till the outdoor temperature is lower than the base temperature and in the case of the cooling system, they continue to supply cooling air if the outdoor temperature is higher than the base temperature. The base temperatures for the four cities are taken from 18 °C to 26 °C. The total numbers of degree-days are calculated as the sum of the number of degree-days for cooling and the number of degree-days for heating, which are calculated using the equations:

$$HDD = \sum_{1}^{N} (T_{base} - \overline{T}_i)$$

$$CDD = \sum_{1}^{N} (\overline{T}_i - T_{base})^+$$

Table 2. Geographical location of the cities (India Meteorological Department (IMD))

City	Latitude	Longitude	Temperature Range (Min-Max)
New Delhi	28.7041° N	77.1025° E	6 °C - 45 °C
Mumbai	19.0760° N	72.8777° E	13 °C - 35 °C
Chennai	13.0827° N	80.2707° E	15 °C - 42 °C
Kolkata	22.5726° N	88.3639° E	11 °C – 41 °C

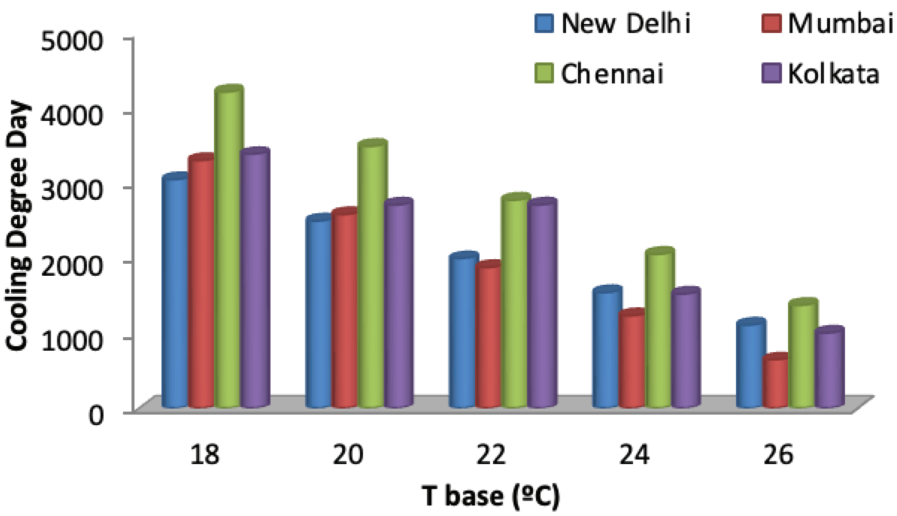

Figure 1. Cooling degree days vs different base temperatures for four cities of India. (obtained using CDD equation).

Where N represents the number of days in heating and cooling.

T_{base} is the reference temperature known as base temperature and T_i represents the mean of daily temperature. The positive subscript indicates only positive values are taken into consideration [45]. The cooling degree days were calculated using the CDD equation for the four cities Mumbai, New Delhi, Kolkata, and Chennai are represented in Figure 1.

Thermal transmittance: thermal transmittance characterizes the thermal performance of the building envelope. Limiting the value of U (W/m^{2}K for the building envelop helps in reducing the heat transfer from the building. Thereby reducing the energy required for the building and improving thermal comfort.

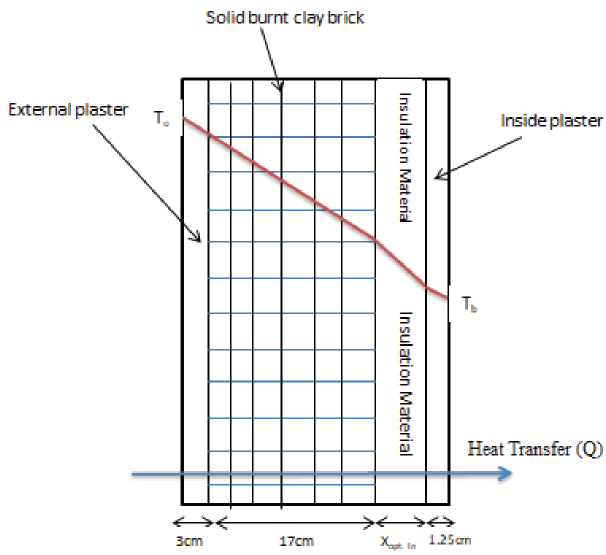

Figure 2. Schematic diagram of sandwich wall and insulation layer.

$$U = \frac{1}{R_t}$$

Model of External Wall for Building Structure

Generally in external wall structures clay brick, concrete with steel reinforced iron bars, stones, and solid concrete blocks are used. The structure of the building's wall depends on the weather of the country. For warm or hot climates only bricks with thin layers of plaster are used and in a cold environment, the composite wall having layers of different material is used. The composite wall consists of layers of material, in which insulation material layers are in the middle of the brick layer and have a thin layer of plaster inside and outside of the wall. In the study, consider the warm climate and the structure of the wall having 1.25 cm plaster inside, 17 cm solid burnt clay brick, and 3 cm plaster outside. Solid burnt clay brick has a density of 1920 kg/m^3, and the thermal conductivity is varied between 0.81 to 0.98 W/mk. the specific heat capacity of the AAC block is 0.79 kJ/kg K. Plaster used in the wall is cement plaster having a thermal conductivity of 0.721 W/mk. In the wall structure, insulation material applies between the surfaces of the wall.

Fiberglass urethane is typically formed by poly-addition reactions of isocyanates with polyols. They are also called Polyurethanes (PU) and are excellent thermal insulating materials. They are widely used in refrigerators, hot water tanks, for insulation and sealing in complex cavities, etc. They are closed and gas filling agents are entrapped within the cavities (Table 3).

Table 3. Insulation material cost and thermal conductivity [46]

Type of Insulation	Thermal conductivity k_{ins} (W/ m °K)	Cost of insulation (₹/m³)
Fiberglass urethane	0.021	15408
Fiberglass rigid	0.033	21888
Urethane rigid	0.024	18864
perlite	0.054	7056
Extruded polystyrene	0.029	10800

Source: market survey *(2020-2021)*

Glass fiber is one of the types of rigid polyurethane foams (RPUFs) fillers and they are analyzed based on kinetics, mechanical and thermal properties. They increase mechanical strength but reduce thermal insulation due to the high thermal conductivity and therefore to keep the thermal at the same level it is preferred to combine the glass fiber with silica because it increases the mechanical strength without compromising with insulating properties (Table 4).

Table 4. Characteristic and application of insulation material [47]

Insulation Material	Characteristic	Application
Glass fiber	water-absorbent, non-combustible, Good workability, low compression resistance	Pipe covering board, blanket, wall
Glass fiber	General-purpose material many facing available	Pipe covering board
Mineral fiber	low compression resistance, water-absorbent, Good workability, non-combustible	Pipe covering board, blanket
perlite	poor Abrasion resistance, Good workability, special packaging required to protect the material from corrosion inhibitors	Pipe and wall covering board
Extruded polystyrene	excellent workability, Lightweight, combustible although some are treated for fire retardancy	Board and blanket

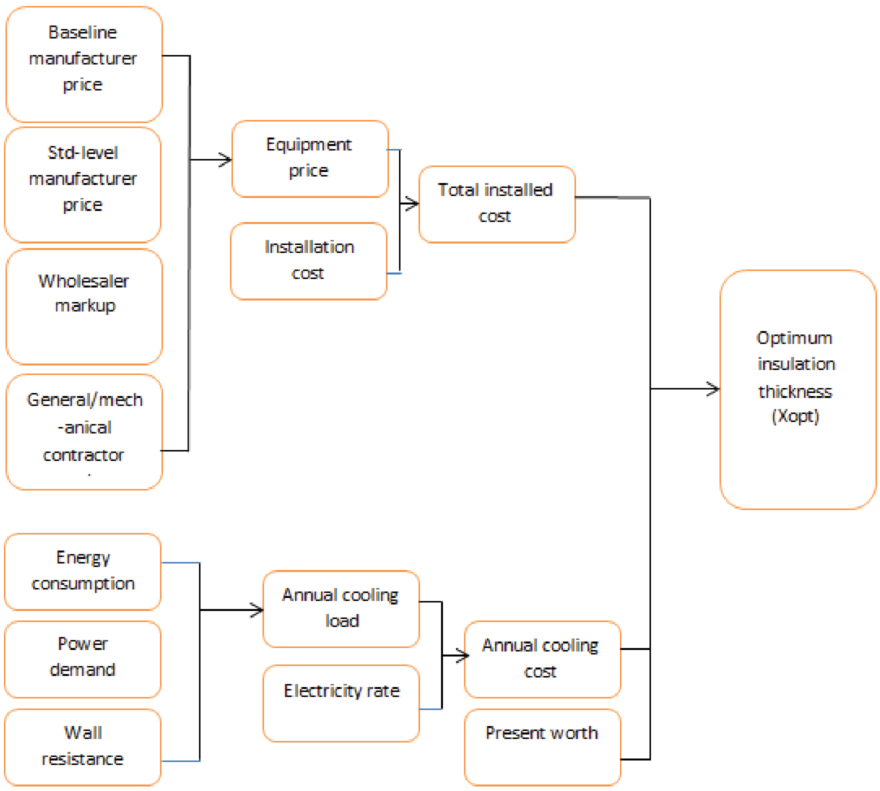

Figure 3. Flow process chart.

Heat Losses Through External Wall

Heat losses from the wall, ceiling, window, and roof are depending on the temperature gradient between outside and inside. We find the optimum wall thickness by considering the energy loss from the building's external wall only.

Heat transfer from the external wall per unit area is, [46]

$$Q = U(T_b - T_o) \tag{1}$$

Boundary conditions;

At x = 0, To = outside mean daily temperature

At x = 21.25 + X_{opt}

Tb = 18°C (its value varies from 18 °C to 26 °C for the different case)

Where U - overall heat transfer coefficient,

T_b - base temperature and

T_o - outside mean daily temperature.

From equation 2, the annual heat loss per unit area from the external wall can be calculated [46],

$$q_A = 86400\,DD\,U \tag{2}$$

The total annual energy [35] requirement is calculated using equation 3,

$$E_A = \frac{86400\,DD\,U}{c.o.p} \tag{3}$$

The overall heat transfer coefficient [46] for an external wall of a building that contains a layer of different material is calculated using equation 4,

$$U = \frac{1}{R_i + R_w + R_{ins} + R_o} \tag{4}$$

Where R_i is the inside air film thermal resistance,

R_o is the outside air film thermal resistance,

R_{wall} is the total thermal resistance of the sandwich wall material.

$R_{insulation}$ is the thermal resistance which is calculated using equation (5) [46],

$$R_{insulation} = \frac{x}{k} \tag{5}$$

x - thickness

k - thermal conductivity of the material.

The annual cooling load is then given by [36],

$$E_A = \frac{86400\,DD}{\left(\frac{x}{k} + R_w\right) c.o.p} \tag{6}$$

The annual cooling cost per unit area [36] is determined by

$$C_A = \frac{86400\,DD\,C_f}{\left(\frac{x}{k} + R_w\right) LHV\ c.o.p} \tag{7}$$

C_f – electricity rate,

LHV – lower heating value,

The cost of insulation is given by

$$C_{ins} = C_i x \tag{8}$$

The total cost of cooling can be calculated for the insulated building in present rupees is given by equation 9,

$$TC = C_A PW + C_i x \tag{9}$$

By minimizing equation 9 using the differentiation method, the optimum insulation thickness x_{opt} [36] is obtained as

$$x_{opt} = 293.94\left(\frac{C_f DDk\ PW}{LHV\ C_i\ c.o.p}\right) - k\ R_w \tag{10}$$

RESULTS AND DISCUSSION

Thermal comfort and corresponding cost savings are achieved by reducing heat transfer from the ceiling and external walls to the surrounding by providing better insulation. For saving more energy, more money needs to spend to add an extra thickness of insulation. Heat transfer from the wall is reduced by applying insulation material. For better performance, Insulation should apply to the inside portion of the wall. As the thickness of the insulation material increases the heat transfer from the wall decreases.

Wood or brick constructs walls have lower heat conductivity than metal and glass, considering thermal perspective. Since buildings are occupied by walls and the overall building heat gain or loss is directly affected by thermal insulation. Insulation is an important factor because it can affect the flow of heat in the building structure and the energy-saving depends on the type of insulating material and the place of insulating material in the wall. Therefore, it should be installed near the location to achieve the best output. In the earlier work, optimum insulation thickness based on HDD is found to be varying between 2 cm to 14 cm for the cold climate like Türkiye and Italy for the different insulation materials. And after applying optimum thickness of insulation material on the building wall in these countries, energy consumption reduces to a great extent and energy can be saved up to 80%, which enhances the building energy performance. In this study, for the case of four climatic zones, the insulation thickness based on CDD varies between 1 cm to 11 cm for the different based temperatures and different insulation materials.

As shown in Table 5, as the base temperature increases, the number of degree days decreases which implies that a less number of days is required for cooling in a year. Hence, decreasing the consumption of energy in the building. Tables 5–8 show that the required optimum insulation thickness for higher degree days is more as compared to lower

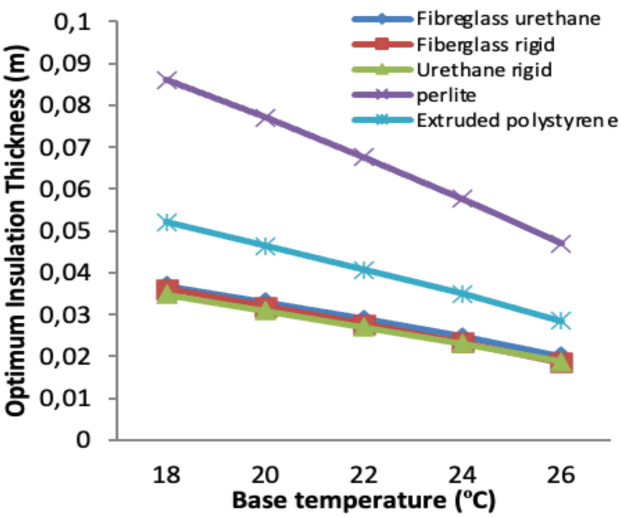

Figure 4. Optimum insulation thickness vs base temperature temperature for for Delhi.

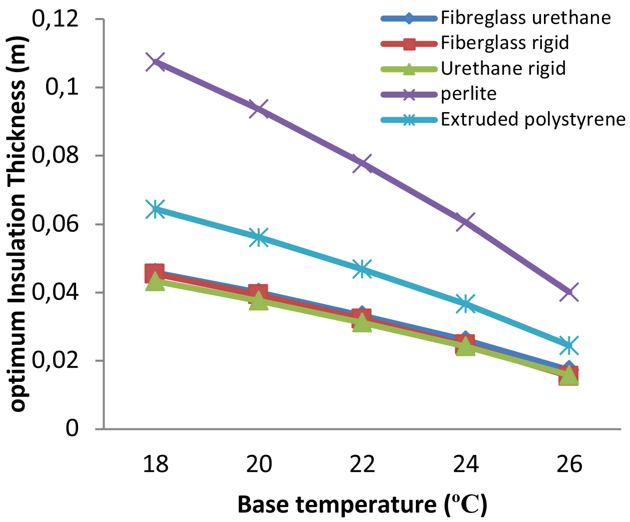

Figure 5. Optimum insulation thickness vs base Mumbai.

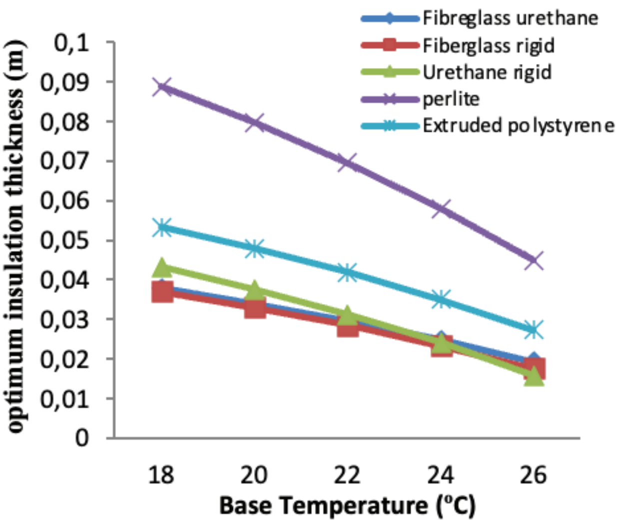

Figure 6. Optimum Insulation thickness vs base temperature for Chennai.

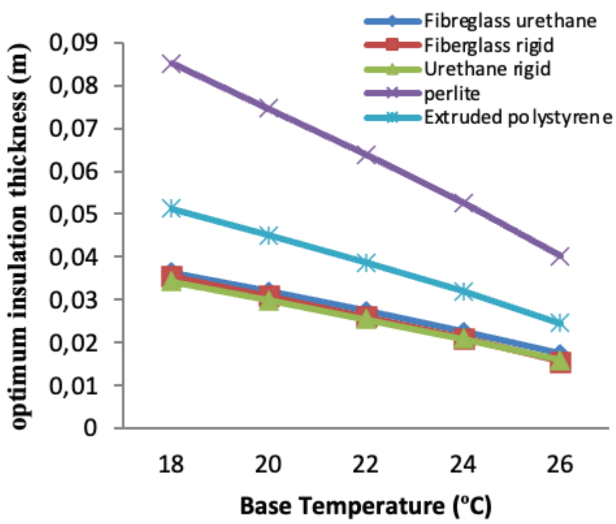

Figure 7. Optimum Insulation thickness vs base temperature for Kolkata.

degree days and also show that optimum insulation thickness decreases with the decrease in the degree day. Figures 4–7 shows that the optimum insulation thickness decreases with the increase in base temperature for different materials and different cities. The figure shows that among the five materials perlite required the highest optimum insulation thickness for the different cities. As the number of degree days decreases, the requirement of insulation thickness for the insulation on the wall also decreases, which reduces the cost of installation. A degree day is an environmental factor, depending on the weather of the city.

As shown from Figures 4–7, we can say that the higher the thermal conductivity, the more the thickness of the insulation material required. Resistance has an inverse relationship with thermal conductivity therefore for increasing the resistance, thickness has to be increased to minimize the heat transfer from the wall. As Table 5 shows that perlite has a higher thermal conductivity as compared to other materials, hence higher optimum insulation thickness is required.

The insulation in the building is a very important criterion to reduce the energy consumption which used in the structure. In the case of Delhi, it has a dry and hot climate. As shown in Table 5, as the base temperature inside the building increases, the required number of days for cooling decreases. In many buildings the base temperature is not constant it may vary with the temperature required for occupants. when the base temperature is 18 °C, the building must go through

Table 5. Optimum Insulation thickness for the New Delhi city

City	Base (T in °C)	CDD	Optimum thickness in meter				
			Extruded polystyrene	Fiberglass rigid	Urethane rigid	perlite	Fiberglass urethane
New Delhi	18	3045	0.0520	0.0361	0.0348	0.086	0.0369
	20	2496	0.0464	0.0319	0.0309	0.0771	0.0329
	22	1995	0.0407	0.0277	0.0270	0.0675	0.0289
	24	1541	0.0349	0.0233	0.0230	0.0577	0.0247
	26	1110	0.0285	0.0185	0.0186	0.0469	0.020

Table 6. Optimum Insulation thickness for Mumbai city

City	Base (T in °C)	CDD	Optimum thickness in meter				
			Extruded polystyrene	Fiberglass rigid	Urethane rigid	perlite	Fiberglass urethane
Mumbai	18	3299	0.0644	0.0454	0.0433	0.1075	0.0458
	20	2582	0.0561	0.0393	0.0376	0.0936	0.0399
	22	1874	0.0468	0.0322	0.0312	0.0777	0.0332
	24	1234	0.0366	0.0246	0.0242	0.06056	0.0260
	26	646	0.02449	0.0155	0.0158	0.0401	0.0173

urethane rigid insulation material which shows minimum optimum thickness among the five different insulation materials. For the case of Delhi, the higher the base temperature, the lower the optimum insulation thickness. As per standard, 24 °C base temperature is the comfort temperature, at 24 °C base temperature inside the building the optimum insulation thickness for extended polystyrene, fiberglass urethane, fiberglass rigid, Urethane rigid, and perlite are 0.0349, 0.0247, 0.0233, 0.0230, and 0.0577m.

In the case of Mumbai, the climate of Mumbai is very humidify which means a lot of moisture is present in the air. Insulation applied to the building structure is based on thermal conductivity and insulation material. As shown in Table 6, the cooling degree days are very high as compared to Delhi but as the climate of Mumbai is not too hot therefore base temperature can be taken more than 22 °C.

As shown in Table 6, as the base temperature decreases the cooling degree days requirement for cooling will decrease, as the cooling degree days decrease the optimum insulation thickness for the insulation material also decreases. The best material for applying on structure based on minimum optimum thickness at 24 °C base temperature is urethane rigid. The thermal conductivity of fiberglass and urethane rigid is is 0.021 and 0.024 W/mK, So for choosing the best material for the insulation of building structure is urethane rigid based on the thickness of insulation, but based on cost and thermal conductivity fiberglass urethane is recommended for the insulation in the building structure because there is very little difference in the optimum insulation thickness of urethane rigid and fiberglass rigid. At 24 °C base temperature inside the building the optimum insulation thickness for extended polystyrene, fiberglass

Table 7. Optimum insulation thickness for Chennai city

City	Base (T in °C)	CDD	Optimum thickness in meter				
			Extruded polystyrene	Fiberglass rigid	Urethane rigid	perlite	Fiberglass urethane
Chennai	18	4213	0.0533	0.0371	0.0433	0.0888	0.0379
	20	3493	0.0479	0.0331	0.0376	0.0797	0.0340
	22	2773	0.0419	0.0286	0.0312	0.0695	0.0297
	24	2055	0.0351	0.0234	0.0242	0.0580	0.0249
	26	1372	0.02736	0.0176	0.0158	0.0449	0.0194

urethane, fiberglass rigid, Urethane rigid, and perlite are 0.0366, 0.0260, 0.0246, 0.0242, and 0.06056m.

For the city Chennai located in the south part of India. The degree day requirement for cooling at a base temperature of 18 °C is 4213 as shown in Table 7. The degree day requirement for cooling for the whole year is more as compared to Delhi and Mumbai as shown in Table 7. Table 7 shows that the perlite material has a large optimal insulation thickness as compared to other materials. It shows high Optimum insulation thickness as compared to other

Table 8. Optimum insulation thickness for Kolkata city

City	Base (T in °C)	CDD	Optimum thickness in meter				
			Extruded polystyrene	Fiberglass rigid	Urethane rigid	perlite	Fiberglass urethane
Kolkata	18	3384	0.0512	0.0355	0.0342	0.0851	0.0363
	20	2709	0.0450	0.0309	0.0299	0.0747	0.0319
	22	2086	0.0386	0.0261	0.0255	0.0639	0.0274
	24	1521	0.0319	0.0211	0.0209	0.0526	0.0226
	26	1004	0.0245	0.0156	0.0159	0.0402	0.0174

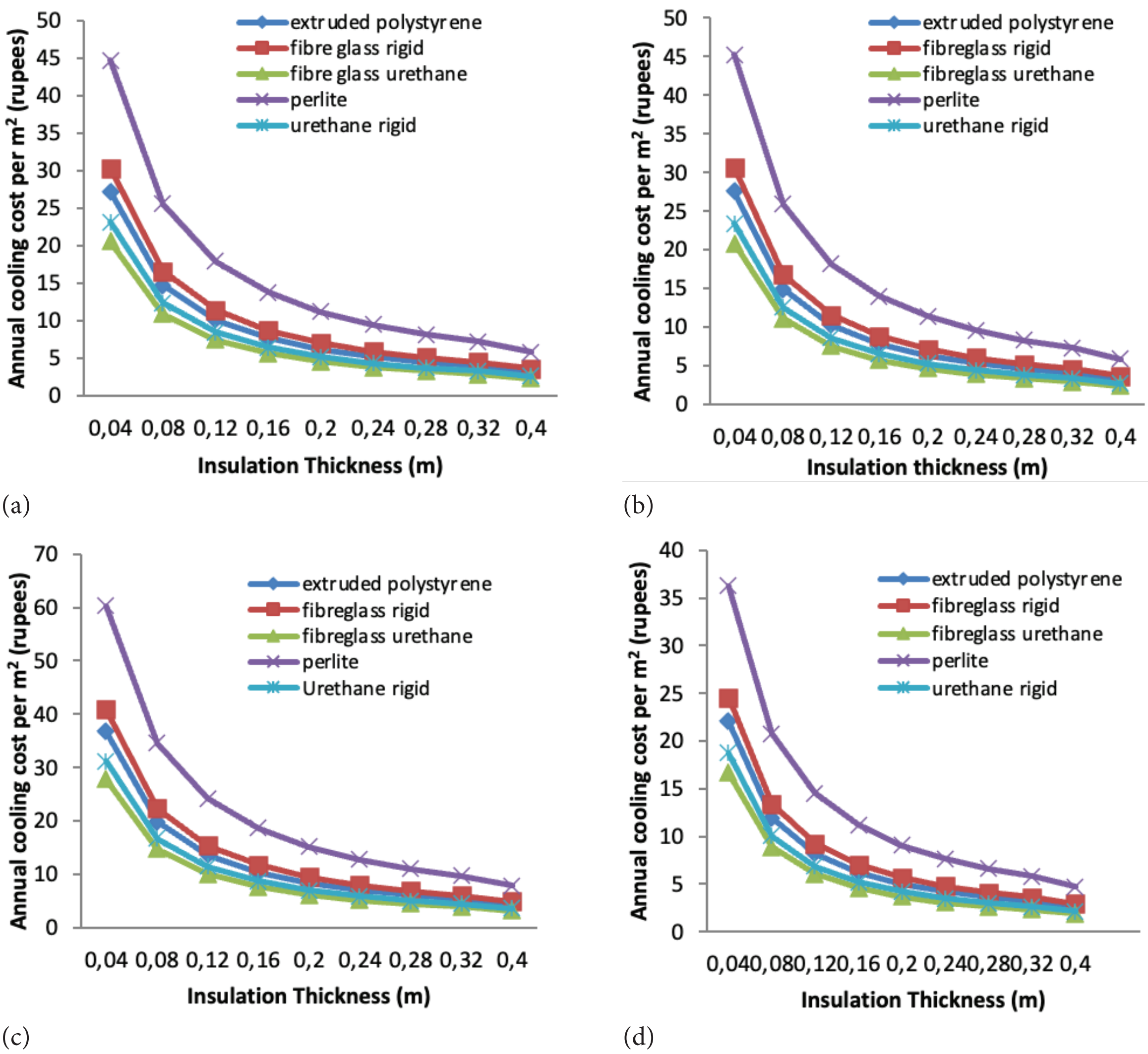

Figure 8. Insulation thickness vs annual cooling cost per m² for different Cities of India at 24 °C base temperature. (a) Kolkata (b) Delhi (c) Chennai (d) Mumbai

materials because the thermal conductivity is very high. The higher the thermal connectivity higher the heat transfer from the building structure. For the case of Chennai, the best insulation material to apply to the building structure is fiberglass rigid.

For the case of Kolkata, the degree-day requirement for cooling for the base temperature 18 °C is 3384. The degree day requirement for Kolkata is between Mumbai and Chennai, the optimum insulation thickness decreases with the increase of base temperature a shown in Table 8. The best insulation material to apply to the building structure is urethane rigid for the case of Kolkata.

From the analysis, it is found that optimum insulation thickness is influenced by cooling degree day and base temperature. And the base temperature is an important parameter in the evaluation of degree days; the base temperature has a significant effect on the cooling degree day through which days required for cooling are affected.

The annual cooling cost for different insulation materials is calculated at 21 °C and 24 °C base temperature as shown in Figures 8 and 9. Figure 8 shows that as the insulation thickness increases the annual cooling cost decrease for different materials and cities. From Figures 8 and 9, it is found that fiberglass urethane insulation material has the least annual cooling cost as compared to other insulation materials for different cities in India. As the base temperature changes, the annual cooling cost varies. The annual cooling cost required for the different insulation materials at 24 °C base temperature is lower as compared to 21 °C base temperature as shown in Figures 8 and 9. Therefore, we conclude that a

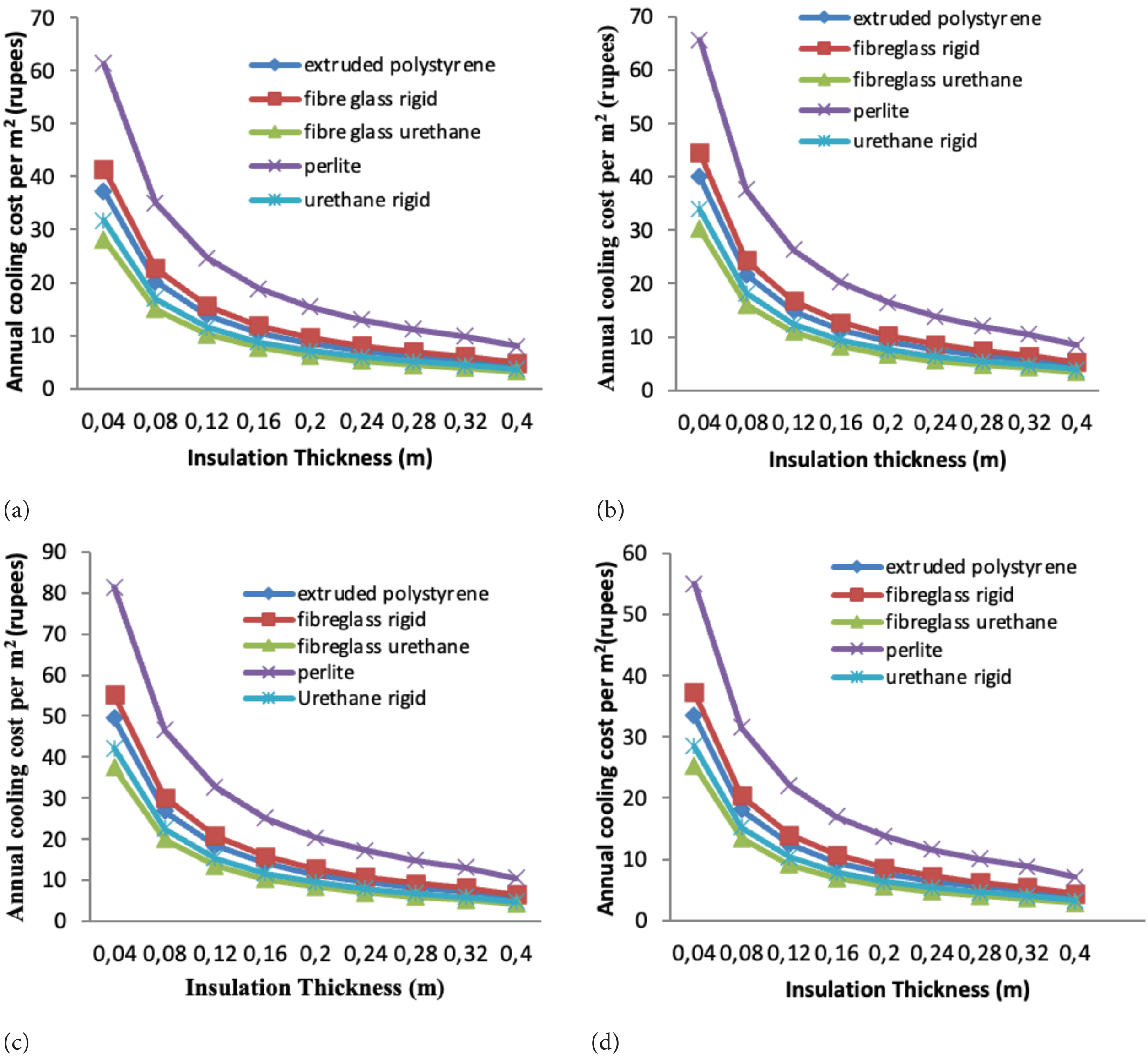

Figure 9. Insulation thickness vs annual cooling cost per m² for different Cities of India at 21 °C base temperature. (a) Kolkata (b) Delhi (c) Chennai (d) Mumbai.

higher base temperature will decrease the annual cooling cost for the building. For the case of different cities in India, it is recommended that among the five materials considered in the study, fiberglass urethane has a low annual cooling cost and the cooling requirement of the building should be considered at 24 degrees Celsius base temperature to achieve an optimal and economical building.

Figure 9 shows that as the insulation thickness increases, the annual cooling cost per m^2 decreases. By increasing the insulation thickness resistance offered by the wall increases which reduces the heat transfer rate from the wall, hence reducing the annual cooling cost per m^2. Annual cooling cost depends on the thermal conductivity of the material, the higher the thermal conductivity of the material higher the annual cooling cost. As from Figure 9, perlite material has a higher annual cooling cost per m^2 and fiberglass urethane has a low annual cooling cost per m^2 as compared to other materials in the different cities of India. Optimum insulation thickness is also depending on the cost of the material and fuel cost. Different state has different fuel cost or electricity tariff rate which influence the optimum insulation thickness. Based on analysis it found that optimum insulation thickness is affected by thermal conductivity, base temperature, CDD, material cost, and fuel cost. For the constant base temperature and cooling degree day, optimum insulation thickness is influenced by the thermal conductivity, material cost, and fuel cost.

CONCLUSION

One of the most important needs for building energy conservation in India is the reduction of energy usage for cooling. Optimum insulation thickness is a function of multiple factors like degree day, electricity cost, and insulation cost, etc. The numerical results revealed how the optimum insulation thickness varies with the climatic condition. When the temperature of the environment is high, the requirement for cooling increases. The electricity cost for one unit differs from city to city. Therefore optimum insulation thickness varies among the city. The optimum insulation thickness is also dependent on the price of the material and fuel cost. In this study, we investigate the influence of base temperature and CDD on insulation thickness for the hot climate of India. The results show that the best suitable insulation material for applying insulation on the external wall at 24 °C for the cities like Delhi, Mumbai, Kolkata, and Chennai are urethane rigid, fiberglass urethane, urethane rigid, and fiberglass rigid respectively, and their corresponding optimum insulation thickness are 0.0270, 0.0260, 0.0209, and, 0.0234 m. Among the five insulation materials, perlite has a higher thermal conductivity as compared to other materials, hence higher optimum insulation thickness is required for all cities. Based on the result, perlite material has the highest annual cooling cost compared to other materials and fiberglass urethane shows the lowest annual cooling cost among the five insulation materials.

Different states have different fuel costs or electricity tariff rates which influences the optimum insulation thickness. As the thickness of wall insulation increases the cooling requirement in the building reduces significantly. Hence, the electricity consumption for cooling the building reduces significantly. But as we increase the insulation thickness, the capital investment for installing the insulation material is also increased. Therefore it is necessary to install insulation material with an optimum thickness for economical energy saving.

In future, various technologies for the development of thermal insulation applied to the building structure are the main research directions for the improvement of building energy performance. The major emphasis should be to enhance the insulation property of material without compromising with the inherent characteristics of that material. The limitation of this study lies in the non-consideration of the building envelope characteristics with the insulation material. In future, this study can be extended for analyzing the insulation efficiency and exergetic performance of different insulation materials.

NOMENCLATURES

U	Overall heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
DD	Degree days (°C days)
K	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)
HDD	Heating degree days
CDD	Cooling degree days
Tb	Base temperature (°C)
Ti	Mean daily temperature (°C)
To	Outside Mean daily temperature (°C)
Cf	Fuel cost in ₹/kWh.
Ci	cost of insulation material (₹/m^3)
x	Insulation thickness (m)
COP	Coefficient of performance
R_o	Outside air film resistance
R_i	inside air film resistance
R_w	Resistance of wall
R_t	Total resistance
LHV	Lower heating value
PW	Present worth
q_a	Heat transfer per unit area
E_A	Annual energy
C_A	Annual cooling cost per unit area
X_{opt}	Optimum insulation thickness (m)

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] International Energy Agency (IEA). 2018 Global Status Report. Available at: https://www.iea.org/reports/2018-global-status-report#overview. Accessed Aug 7, 2024.

[2] Shahid M, Karimi MN. Optimization of energy transmittance through building envelope for hot dry climate. J Therm Engineer 2022;8:595-605. [CrossRef]

[3] Durmayaz A, Kadioglu M, Sen Z. An application of the degree-hours method to estimate the residential heating energy requirement and fuel consumption in Istanbul. Energy 2000;25:1245-1256. [CrossRef]

[4] Buyukalaca O, Bulut H, Yilmaz T. Analysis of variable-base heating and cooling degree-days for Turkey. Appl Energy 2001;69:269-283. [CrossRef]

[5] Granja AD, Labaki LC. Influence of external surface color on the periodic heat flow through a flat solid roof with variable thermal resistance. Int J Energy Res 2003;27:771-779. [CrossRef]

[6] Kaynakli O. A review of the economical and optimum thermal insulation thickness for building applications. Renew Sustain Energy Rev 2012;16:415-425. [CrossRef]

[7] Aditya L, Mahlia TMI, Rismanchi B, Ng HM, Hasan MH, Metselaar HSC, et al. A review on insulation materials for energy conservation in buildings. Renew Sustain Energy Rev 2017;73:1352-1365. [CrossRef]

[8] Zedan MF, Mujahid AM. An efficient solution for heat transfers in composite walls with periodic ambient temperature and solar radiation. Int J Ambient Energy 1993;14:83-98. [CrossRef]

[9] Al-Obaidi AR. Investigation of fluid field analysis, characteristics of pressure drop and improvement of heat transfer in three-dimensional circular corrugated pipes. J Energy Storage 2019;26:101012. [CrossRef]

[10] Al-Obaidi AR, Sharif A. Investigation of the three-dimensional structure, pressure drop, and heat transfer characteristics of the thermohydraulic flow in a circular pipe with different twisted-tape geometrical configurations. J Therm Anal Calorim 2021;143:3533-3558. [CrossRef]

[11] Al-Obaidi AR. Analysis of the flow field, thermal performance, and heat transfer augmentation in circular tube using different dimple geometrical configurations with internal twisted-tape insert. Heat Transf 2020;49:4153-4172. [CrossRef]

[12] Al-Obaidi AR, Alhamid J. Numerical investigation of fluid flow, characteristics of thermal performance and enhancement of heat transfer of corrugated pipes with various configurations. J Phys Conf Ser 2021;1733:012004. [CrossRef]

[13] Al-Obaidi AR. Study the influence of concavity shapes on augmentation of heat-transfer performance, pressure field, and fluid pattern in three-dimensional pipe. Heat Transf 2021;50:4354−4381. [CrossRef]

[14] Al-Obaidi AR. Investigation of the flow, pressure drop characteristics, and augmentation of heat performance in a 3D flow pipe based on different inserts of twisted tape configurations. Heat Transf 2021;50:5049−5079. [CrossRef]

[15] Al-Obaidi AR, Chaer I. Study of the flow characteristics, pressure drop and augmentation of heat performance in a horizontal pipe with and without twisted tape inserts. Case Stud Therm Eng 2021;25:100964. [CrossRef]

[16] Alhamid J, Al-Obaidi AR. Effect of concavity configuration parameters on hydrodynamic and thermal performance in 3D circular pipe using Al2O3 nanofluid based on CFD simulation. J Phys Conf Ser 2021;1845:012060. [CrossRef]

[17] Alhamid J, Al-Obaidi RA. Flow pattern investigation and thermohydraulic performance enhancement in three-dimensional circular pipe under varying corrugation configurations. J Phys Conf Ser 2021;1845:012061. [CrossRef]

[18] Al-Obaidi AR, Alhamid J, Hamad F. Flow felid and heat transfer enhancement investigations by using a combination of corrugated tubes with a twisted tape within 3D circular tube based on different dimple configurations. Heat Transf 2021;50:6868-6885. [CrossRef]

[19] Al-Obaidi AR, Alhamid J. Investigation of flow pattern, thermohydraulic performance and heat transfer improvement in 3D corrugated circular pipe under varying structure configuration parameters with development different correlations. Int Commun Heat Mass Transf 2021;126:105394. [CrossRef]

[20] Al-Obaidi AR. Investigation on effects of varying geometrical configurations on thermal hydraulics flow in a 3D corrugated pipe. Int J Therm Sci 2022;171:107237. [CrossRef]

[21] Alola AA, Bekun FV, Sarkodie SA. Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. Sci Total Environ 2019;685:702-709. [CrossRef]

[22] Alola AA, Saint Akadiri S, Akadiri AC, Alola UV, Fatigun AS. Cooling and heating degree days in the US: The role of macroeconomic variables and its impact on environmental sustainability. Sci Total Environ 2019;695:133832. [CrossRef]

[23] Saint Akadiri S, Alola AA, Alola UV, Nwambe CS. The role of ecological footprint and the changes in degree days on environmental sustainability in the USA. Environ Sci Pollut Res Int 2020;27:24929-24938. [CrossRef]

[24] Spinoni J, Vogt JV, Barbosa P, Dosio A, McCormick N, Bigano A, et al. Changes of heating and cooling degree-days in Europe from 1981 to 2100. Int J Climatol 2018;38:e191-208. [CrossRef]

[25] Al-Hadhrami LM. Comprehensive review of cooling and heating degree days characteristics over Kingdom of Saudi Arabia. Renew Sustain Energy Rev 2013;27:305-314. [CrossRef]

[26] Moazami A, Nik VM, Carlucci S, Geving S. Impacts of future weather data typology on building energy performance - Investigating long-term patterns of climate change and extreme weather conditions. Appl Energy 2019;238:696-720. [CrossRef]

[27] Moreci E, Ciulla G, Lo Brano V. Annual heating energy requirements of office buildings in a European climate. Sustain Cities Soc 2016;20:81–95. [CrossRef]

[28] Christenson M, Manz H, Gyalistras D. Climate warming impact on degree-days and building energy demand in Switzerland. Energy Conver Manage 2006;47:671-686. [CrossRef]

[29] Zinzi M, Carnielo E, Mattoni B. On the relation between urban climate and energy performance of buildings. A three-years experience in Rome, Italy. Appl Energy 2018;221:148-160. [CrossRef]

[30] Ramon D, Allacker K, De Troyer F, Wouters H, van Lipzig NP. Future heating and cooling degree days for Belgium under a high-end climate change scenario. Energy Build 2020;216:109935. [CrossRef]

[31] D'Amico A, Ciulla G, Panno D, Ferrari S. Building energy demand assessment through heating degree days: The importance of a climatic dataset. Appl Energy 2019;242:1285-1306. [CrossRef]

[32] Mohsen MS, Akash BA. Some prospects of energy savings in buildings. Energy Conver Manage 2001;42:1307-1315. [CrossRef]

[33] Jaber JO. Prospects of energy savings in residential space heating. Energy Buildings 2002;34:311-319. [CrossRef]

[34] Al-Sallal KA. Comparison between polystyrene and fiberglass roof insulation in warm and cold climates. Renew Energy 2003;28:603-611. [CrossRef]

[35] Comakli K, Yuksel B. Optimum insulation thickness of external walls for energy saving. Appl Therm Engineer 2003;23:473-479. [CrossRef]

[36] Bolatturk A. Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey. Appl Therm Engineer 2006;26:1301-1309. [CrossRef]

[37] Bademlioglu AH, Canbolat AS, Turkan B, Kaynakli O. Investigation of optimum thermal insulation thickness depending on solar radiation and wall directions. 4th Anatolian Energy Symposium with International Participation; 2018. pp. 2156-2164.

[38] Cay Y, Gurel AE. Determination of optimum insulation thickness, energy savings, and environmental impact for different climatic regions of Turkey. Environ Prog Sustain Energy 2012;32:365-372. [CrossRef]

[39] Kurekci NA. Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers. Energy Build 2016;118:197-213. [CrossRef]

[40] Dombayci OA, Atalay O, Acar SG, Ulu EY, Ozturk HK. Thermoeconomic method for determination of optimum insulation thickness of external walls for the houses: Case study for Turkey. Sustain Energy Technol Assess 2017;22:1-8. [CrossRef]

[41] Pinak R, Geeta B. Estimation of power generation from solid waste generated in sub-urban area using spatial techniques: A case study for Pune City, India. Int J Geomatics Geosci 2011;2:179–187.

[42] Remme U, Trudeau N, Graczyk D, Taylor P. Technology development prospects for the Indian power sector. Available at: https://www.iitr.ac.in/wfw/web_ua_water_for_welfare/water/WRDM/IEA-Tech_Dev_Indian_Pow_Sect_2011.pdf. Accessed Aug 7, 2024.

[43] Shanmuga Priya S, Migadalska J. Cooling degree day analysis as a climate Impact Indicator for different locations of Poland and India. Int J Adv Sci Engineer Technol 2016;3:42-50.

[44] Shanmuga Sundaram A, Bhaskaran A. Optimum insulation thickness of walls for energy-saving in hot regions of India. Int J Sustain Energy 2014;33:213-226. [CrossRef]

[45] American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2009 ASHRAE handbook - Fundamentals.Available at: https://shop.iccsafe.org/media/wysiwyg/material/8950P217-toc.pdf. Accessed Aug 7, 2024.

[46] Cengel Y, Ghajar A. Heat and Mass Transfer: Fundamentals and Applications. New York: McGraw Hill Inc; 2010.

[47] Ministry of Power, Government of India. Energy conservation building code of India 1017. Available at: https://beeindia.gov.in/sites/default/files/BEE_ECBC%202017.pdf. Accessed Aug 7, 2024.