Calculate optimum insulation thickness to all over Indian city and compare it with the degree day method

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Abstract: The study is done on 60 cities from different climatic zones of India. Thermal insulation is an essential parameter in the building sector to save energy and money. This research focuses on using five insulation materials (extruded polystyrene, expanded polystyrene, glass wool, rock wool, and polyurethane). It investigates the effect of the insulation material's thermophysical properties in saving energy, life cycle cost, and payback period. The calculation is conducted using five different (coal, oil, gas, natural gas, and electric) fuels. The energy calculation is done using a heat balance algorithm. The results are compared and verified with the degree day method. EnergyPlus software is used to validate the results for the sixty cities selected. The difference in energy efficiency savings between these two methods is analysed to determine the potential error of each method.

Keywords: degree day; DD; EPS; XPS; PUF; GW; RW; life cycle cost; payback period.

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1 Introduction

The subcontinent of India has abundant sources of both exhaustible and renewable energy resources. The most commonly used commercial energy sources are fossil fuels, coal, oil, and natural gas. However, they are also significant contributors to the high pollution rate of India. IPCC working group is responsible for assessing climate change mitigation by reducing emissions and enhancing sinks of greenhouse gases responsible for global warming. In India, the IPCC meeting held in Delhi in 2019 reported that the most important factor accountable for the degradation of the country's climatic changes is global warming, after assessing the energy, agriculture, forestry, land use, transport, and building sectors.

Energy consumption is divided into four sections: residential, commercial, transportation, and industrial in India. The residential or building sector alone consumes about 30–40% of the total electricity. That is why most researchers of recent times have focused on reducing energy consumption through the passive method. Mohsen and Akash (2001) conducted a survey in the residential sector on energy consumption in Jordan, using kerosene for heating purposes, which is the popular fuel. They used different insulation materials for saving energy and concluded that when polystyrene is used in both walls and roofs, up to 76.8% savings of energy is possible. Turkey has four different kinds of weather, so Bollaturk (2006), in their work, chose 16 cities from each weather location. He used polystyrene as an insulation material in the building with different fuel types. He tried to optimise the building insulation in terms of saving energy, payback period, and life cycle cost analysis. The important factor is determining heat loss characteristics and using proper insulation material to save energy. For this purpose, a prototype building was used in Bursa. The work was done using the Degree day (DD) method used to calculate energy consumption in the building. The optimum insulation thickness varies between 5.3–12.4 cm depending on the type of fuel used. Kurekci et al. (2009) and Nuri (2016) divided Turkey's climate zone into four parts depending on the average temperature DD and applied insulation material and evaluated that about 33% of energy is consumed in the residential sector. The calculation of optimum thickness value is based on using six different energy fuel, i.e., soma coal, natural gas, coal, LPG, fuel oil, diesel and, two insulation material (extruded polystyrene, rock wool). The optimum insulation thickness (EPS and XPS) is calculated using different construction materials: concrete, briquette, brick, blokbims, and autoclaved aerated concrete (AAC) for insulated and un-insulated wall structures. The investigation is carried out on the south-facing wall. Results show that optimum thickness varies 2–8.2 cm, and energy-saving is possible up to 2.78 and \$102.16/m^2; results are compared with the DD method (Meral, 2011). Ashok and Suman (2013) work on the different Indian weather zone and use automatic guarded hot plate apparatus to calculate the different insulation materials' thermal conductivity and check the building energy performance's thermal performance. Recently, different natural materials are being used to work as insulation material. Belhadj et al. (2015) used barley straws (SC W BS) as an insulation material in their work. The authors focused on its thermophysical properties, wall thickness, air gap within the wall, wall orientation, as well as a surface coating on the time lag and decrement factor of the material. Ayaz et al. (2019) also investigating natural materials such as sheep wool, goat wool, and horse mane and characterising their properties such as moisture absorption, thermal conductivity, thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). Maryam et al. (2019) worked on bio-gradable material as thermal insulation material in the building. The study focused on using hemp as an insulation material in a building in Morocco. Time lag and decrement factors are accessed in order to determine the dynamic behaviour of multilayer insulation material.

Thermal insulation plays a vital role in developing different policies depending on the concept of generating efficiency. Based on energy demand and the people's demand for a comfortable environment, using insulation material in the building reduces energy load, but increasing insulation material steadily and investigating its effect on cumulative cooling load has less effect while greatly impacting heating load (Lili et al., 2019). Amiri and Elmira (2019) calculated optimum insulation thickness based on energy, environment, and economics using mineral wool. Recently, work is focused on developing thermal insulation material for the construction and production industry based on cost-effective energy conservation. For improving thermal insulation, a key problem is selecting insulation material for a particular location and load because it is difficult to setup a balance in both energy-saving and economic friendly. Haukun et al. (2020) selected a novel material aerogel super insulation material for improving building energy conservation. This new composite was also used as a prefabricated wall block (CPWB) (Behrooz et al., 2020) to calculate optimum insulation thickness using the DD method and life cycle cost analysis. The research work was conducted using the most common insulation material and investigated the correct position of insulation material in-wall, so o to up to 12 cm thickness were considered for the test. Results concluded that its best position in the wall is in the middle of the building wall envelope. Structural insulation panel products play a vital role in the decrement of energy consumption, and further improvement can be made by adding its potential energy performance, which is a vacuum insulation panel (Raimundo et al., 2020). Amani and Kiaee (2020) gave a design of an optimum insulation system using a multi-objective optimisation technique to maximise energy-saving and minimise environmental degradation, using 12 different insulation materials with different thicknesses. They also proposed four layers of insulation system (Geng et al., 2021). A classic grey brick wall and three modern walls (hollow clay block, LECA block and AAC block) were selected for building construction and applied insulation material. Rosti et al. (2020) from Iran worked on the effect of orientation of the building wall in their research. The study revealed that maximum insulation thickness is 4cm which is lower as compared to other countries. Sustainable insulation material could be able to delay peak temperature inside the building and reduce overheating effects during the summer period. This analysis shows that low thermal resistance effectively works during the winter season, and higher thermal resistance is cost-effective during the winter season (high thermal resistance is not suitable, the study revealed) (Kumar et al., 2020; Adityaa et al., 2017). In their work, R.F.J. Alberto and F.D. Rosas selected five different insulation materials (EPS, XPS, GW, RW and PUF) and applied them to the buildings' walls and roofs. The study revealed that approximately 95% of the households in Mexico do not have thermal insulation in the buildings. Applying insulation material for all existing and future projects till 2030 can save energy up to 94.72 TWh, which is about 44.67 MM tons CO_2 (Rosas-Flores and Rosas-Flores, 2020). Fallah and Medghalchi (2020) have stated that anti insulation is the reason that cooling energy consumption increases after applied thermal insulation material. They focused on using proper insulation material for particular energy demands. Polyurethane insulators, polystyrene, rockwool, and glass-wool, have the highest heating and total energy saving, respectively, and vice-versa for the cooling load (Mehmat et al., 2018). Kaynakli (2008, 2012) used three insulation materials (polyurethane, extruded polystyrene, and mineral wool) used and developed a life cycle assessment over 50 years, and analysed the environmental effect of each insulation material. The study revealed that the highest environmental impact was delivered by polystyrene and the best performance was with mineral wool. However, all insulation materials have the same thermal performance during the whole year (Llantoy et al., 2020).

2 Objective

The most important parameter is finding out the transition of heat in the wall, roof, window opening, void, air infiltration, etc. The optimum calculation is based on life cycle cost, payback period, and energy savings in this study. The study has two parts. In the first part, the energy calculation based on optimum thickness using the DD method is done. In the second part, the software EnergyPlus is used to calculate the optimum thickness. In the DD method, the calculations are done by the author manually. The estimates are based on the assumption that heat transient takes place only through the wall section.

The DD method is essentially based on equilibrium temperature between indoor and outdoor temperature. Indoor temperature (setpoint temp) is different from building to building and location to location. Thus, removing complication in the calculation, an approximate temperature is considered, i.e., 18°C as base temperature, but in simulation, 22°C setpoint temperature is considered. DD method calculates annual heating and cooling load (data depends on a particular location and available information). There is an approximate method to regularly calculate building energy load because of the temperature difference between indoor and outdoor. The focus must be on solar heat gain, sky radiation gain, building position, and other factors to get an accurate result. However, several researchers conclude that it is an approximate method to calculate energy saving and control environment degradation levels. The approximate calculation is based on comparing the selected city results obtaining through the DD method and simulated results.

Table 1 Indian climate zone as per ASHRAE standard 169-2013

Climate Zones of India (per ASHRAE Standard 169-2013)		*Number of cities*
0A	15	
Extremely hot-dry	0B	10
Very hot-humid	1A	14
Very hot-dry	1B	11
Hot-humid	2A	7
Hot-dry	2B	1
Warm-marine	3C	1
Mixed-humid	4A	1

The EnergyPlus software is a dynamic simulation tool (US Department of Energy) to simulate the building's thermal load. Appropriate selection of weather data is an important component of evaluating energy efficiency through building energy simulation. In this paper, five different insulation materials are used: EPS, XPS, PUF, GW, and RW, and six cities are selected for analysis of these insulation materials' thermal performance. The Indian climatic zone is explained in ASHRAE 169-2013 briefly, as shown in Table 1.

Table 2 explained the details of world weather zones, in which weather is divided into 12 zones. However, according to ASHRAE standard 169, climate data for building construction is divided into nine thermal zones. India is a country where an all-weather zone exists, and it is clarified after comparing Tables 1 and 2.

Table 2 World weather climate description (as per ASHRAE standard 169 books guidelines)

Thermal zones	*Name*	*Degree day*
0	Extremely hot-humid (0A), dry (0B)	6,000 < CDD10°C
1	Very hot-humid (1A), dry (1B)	5,000 < CDD10°C ≤ 6,000
2	Hot-humid (2A), dry (2B)	3,500 < CDD10°C ≤ 5,000
3A and 3B	Warm-humid (3A), dry (3B)	2,500 < CDD10°C < 3,500 AND HDD18°C ≤ 2,000
3C	Warm-marine (3C)	CDD10°C ≤ 2,500 AND HDD18°C ≤ 2,000
4A and 4B	Mixed-humid (4A), dry (4B)	1,500 < CDD10°C < 3,500 AND 2,000 < HDD18°C ≤ 3,000
4C	Mixed-marine	CDD10°C ≤ 1,500 AND 2,000 < HDD18°C ≤ 3,000
5A and 5B	Cool-humid (5A), dry (5B)	1,000 < CDD10°C ≤ 3,500 AND 3,000 < HDD18°C ≤ 4,000
5C	Cool-marine (5C)	CDD10°C ≤ 1,000 AND 3,000 < HDD18°C ≤ 4,000
6A and 6B	Cold-humid (6A), dry (6B)	4,000 < HDD18°C ≤ 5,000
7	Very cold (7)	5,000 < HDD18°C ≤ 7,000
8	Subarctic/arctic (8)	7,000 < HDD18°C

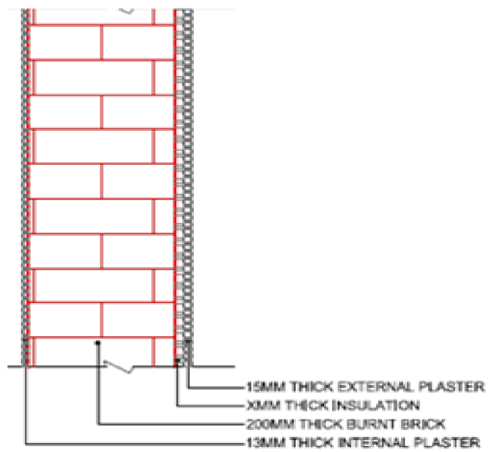
So it is a better way to analyse the application of these insulation materials in India for different climatic zones since India's unique position on the globe makes it susceptible to all weather conditions prevalent around the globe. India's different physical locations experience diverse climatic conditions like composite, hot and dry, warm and humid, temperature and cold climatic all the year-round. Therefore, this study is not just applicable to Indian region, but can also be used for any location in the world with similar conditions.

3 Methodology

3.1 The structure of the wall

Heat loss and gain occur through the wall, roof, window, void gap, and air filtration. This study considered only walls to calculate heat transient conduction, taking a hint from Wei et al.'s (2018) work between indoor and outdoor environments. Basically, this study has two-part, in one part calculate optimum insulation thickness through EnergyPlus (a dynamic simulation software, US Department of Energy) and the other one using DD methods. After calculating insulation thickness from both of the methods, compare with them. The optimum insulation thickness is based on three important factors: total cost/m^2, payback period, and energy saving. For this study, five different insulation materials were used (EPS, XPS, PUF, GW and RW), and the properties of these are described in the table. The wall structure is shown in fig and in this wall using insulation material one by one and investigates these on the building loads.

Figure 1 Inside building wall structure (see online version for colours)



3.2 DD methods

DD values depend on the equilibrium between inside and outside environment, i.e., there is no requirement for heating and cooling inside the building zone. The equilibrium temperature different from building to building and location to location, so this study considered 18°C as a base temperature for calculating HDD and CDD. Mainly heating and cooling DD is different. The insulation material is applied outside of the wall and then applying plaster, as shown in Figure 1, and the wall properties (Daouas, 2016) are explained in Table 3.

As per ASHRAE 2009, the DD is the difference between indoor average temperature and outdoor base temperature, and the formula suggested is shown below in equations (1) and (2). The heating and cooling degree for all cities in India is tabulated in table.

$$HDD_d = T_b - \frac{T_m + T_{\min}}{2} \tag{1}$$

$$CDD_d = \frac{T_m + T_{\min}}{2} - T_b \tag{2}$$

where T_m is daily maximum temperature and $T_{\min}$ is daily minimum temperature.

Table 3 Thermal property of materials

Materials	*k (W/mK)*	*ρ (kg/m³)*	*α × 10⁷ (m²/s)*
Brick (230 mm)	0.69	2,049	3.98
Roof	0.23	1,150	2
Stone	1.7	2,500	6.8
Cement plaster	1.4	2,200	6.3
Cement lime plaster	1	1,900	5.26
Concrete	1.65	2,000	8.25
Reinforced concrete	2.5	2,400	10.41

Table 4 Heating and cooling DD for all cities in India

No.	*City*	*HDD*	*CDD*
1	Ahmedabad	3,580	8
2	Akola	3,440	5
3	Allahabad	2,933	145
4	Amritsar	2,380	420
5	Aurangabad	2,845	1
6	Barmer	3,500	45
7	Belgaum	2,345	0
8	Bengaluru	2,345	0
9	Bhagalpur	3,245	10
10	Bhopal	2,855	72
11	Bhubaneshwar	3,468	0
12	Bhuj	3,482	25
13	Bikaner	3,300	278
14	Chennai	3,997	0
15	Chitradurga	2,670	0
16	Dehradun	1,845	345
17	Dibrugarh	1,878	205
18	Gorakhpur	2,823	135
19	Guwahati	2,300	78
20	Gwalior	3,001	278
21	Hisar	3,256	220
22	Hyderabad	3,256	0
23	Imphal	1,345	489
24	Indore	2,641	28
25	Jabalpur	2,713	75
26	Jagdalpur	2,415	21
27	Jaipur	3,078	152
28	Jaisalmer	3,678	92

Table 4 Heating and cooling DD for all cities in India (continued)

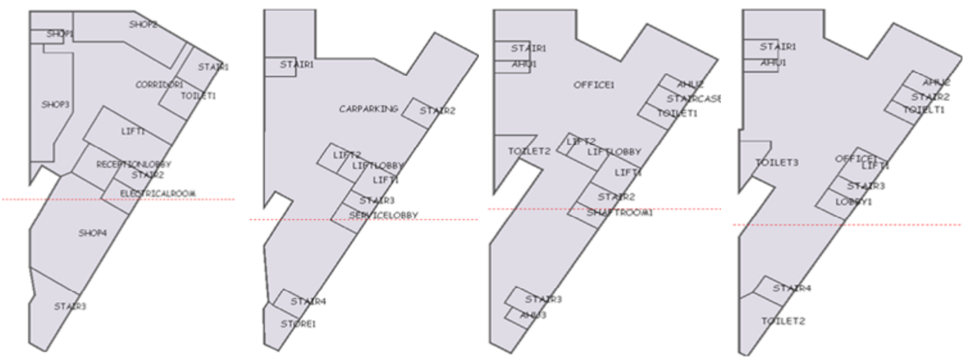
No.	*City*	*HDD*	*CDD*
29	Jamnagar	2,893	21
30	Vishakhapatnam	3,651	0
31	Jodhpur	3,780	49
32	Jorhat	2,208	139
33	Kolkata	3,257	9
34	Kota	3,425	89
35	Kurnool	3,942	0
36	Lucknow	2,934	159
37	Mangalore	3,470	0
38	Mumbai	3,578	0
39	Nagpur	3,289	1
40	Nellore	4,155	0
41	New Delhi	2,935	278
42	Panjim	3,479	0
43	Patna	2,678	120
44	Pune	2,345	12
45	Raipur	3,245	8
46	Rajkot	3,689	4
47	Ramagundam	3,789	0
48	Ranchi	2,240	178
49	Ratnagiri	3,642	0
50	Raxaul	2,489	178
51	Saharanpur	2,135	478
52	Shillong	150	1,789
53	Solapur	3,897	0
54	Srinagar	780	2,025
55	Surat	3,457	0
56	Tezpur	2,546	48
57	Thiruvananthapuram	3,579	0
58	Tiruchirappalli	4,263	0
59	Varanasi	3,248	158
60	Veraval	3,489	0

Table 4 present all states heating and cooling DD. Figure 1 show the basic structure of the building, polyline constructed in design builder software. In the building have four floor total building floor area is 9,645.79 m^2. The external wall of the building is constructed with 15 mm external cement, 230 mm red brick, x mm internally insulated and then applying 12.5 mm internal cement. In this study using five different type of insulation and their thermal properties are present in Table 5.

Table 5 Selected insulation material characteristics

Insulation	*ρ (kg/m³)*	*Thermal conductivity k (W/mk)*	*Cost in \$/m³*
EPS	25	0.04	120
XPS	30	0.0321	180
PUF	36	0.0372	260
GW	16	0.035	75
RW	150	0.045	80

Figure 2 Shape of building floor wise, (a) 1 first floor (b) 1 second floor, (c) 1 third floor (d) 1 fourth floor (design builder images) (see online version for colours)



3.3 Heating and cooling load calculation

Heat flux to transfer heat from and to the external wall is calculated by using equation (3)

$$q = U \times \Delta t \tag{3}$$

U is the heat transfer coefficient (W/m²K). While Δt is the temperature difference between the inside and outside temperature of the building, the building's annual heating loss or gain occurring through the wall is calculated with the U value's help. The DD is calculated by using equations (4) and (5)

$$q_{year}, H = 86,400 \times HDD \times U \tag{4}$$

$$q_{year}, C = 86,400 \times CDD \times U \tag{5}$$

Total overall heat transfer coefficient. A typical wall is

$$U = \frac{1}{R_i + R_w + R_{ins} + R_o} \tag{6}$$

R_i, R_o is the inside and outside heat transfer coefficient and R_{ins}, is the thermal insulation of insulant, and R_w is the wall heat transfer coefficient.

$$R_s = \frac{x}{k} \tag{7}$$

$$R_{w,t} = R_i + R_w + R_t \tag{8}$$

X is the unknown thermal insulation material thickness, and k is the insulation material's thermal conductivity.

Annual heating and cooling energy as follow as equations (9) and (10)

$$E_{year}, H = \frac{86,400 * HDD}{(R_{w,t} + R_{ins}) * n} \tag{9}$$

$$E_{year}, C = \frac{86,400 * CDD}{(R_{w,t} + R_{ins}) * COP} \tag{10}$$

$$r = \frac{i - g}{t + g} \tag{11}$$

$$PWF = \frac{(1+N)^N - 1}{r * (1+r)^N} \tag{12}$$

PWF helps to calculate the approximate energy consumption cost of the building over a 20-year life span. Hence, the life cycle cost of the building per unit area, including PWF with the insulation of the building, is calculated by using equation (13).

$$C_t = C_{energy} + C_{ins} = PWF * \left(\frac{Q_c}{COP} \frac{Cel}{3.6 * 10^6} + \frac{Q_h}{Hu \cdot ns} C_g \right) + L_{ins} * C_y \tag{13}$$

The payback period (b) is the number of years needed to return the amount of expenditure used in the construction of the building. This amount is available in the form of energy-saving after applying insulation materials, as is clearly understood from equation (14)

$$\begin{cases} b = \dfrac{L_n \left[1 - (g - i) C_{ins} L_{ins}\right]}{L_n * \left(\dfrac{1+i}{1+g} \right)} & i \neq g \\ b = (1+i) \dfrac{C_{ins} L_{ins}}{A_s} & i = g \end{cases} \tag{14}$$

where A_s is the annual energy saving; $A_s = C - C_t$. Annual saving is the difference between the annual energy cost without insulation to the energy cost with insulation. Table 6 illustrates all the relevant data used in getting the results from equations (11)–(14).

The optimum insulation thickness for minimum heating and cooling is calculated with the help of the equation below (Kaynakli, 2008, 2012)

$$X_{opt,H,C} = 293.94 \times \left(\frac{HDD * C_f * PWF * k}{Hu * C_y * n} + \frac{CDD * PWF * k * C_e}{C_y * COP} \right)^{0.5} - R_{w,t} * k \tag{13}$$

Table 6 Parameter used in calculations

Interest rate (*i*)	8%
Inflation rate (*g*)	7.5%
Life span (*N*)	25
PDF	9.05

4 Dynamic energy simulation

The thermal behaviour of the wall is evaluated employing EnergyPlus software, which is very dynamic. This software is capable of calculating the thermal load needed for human comfort and also calculates the heat conduction through the wall by using conduction transfer function (CFT) methods. Simulation is done using the weather data, which is in typical meteorological year (TMY) format. The weather file is available in ISHRAE society. This weather file is collected from the last 10–30 years survey and the content designed for day data and location details. The CTF method was used to optimise the building energy load, and it requires less effort to solve the complicated calculation. The CTF method used in this study has validated the results (Daouas, 2016). The parametric run is available in the EnergyPlus software, which is reduced the time to feed the different thicknesses in every run. Through this feed, the thickness range from min to max easily calculates all energy loads accordingly.

5 Results and discussion

After continuous increment of insulation thickness, directly increasing installation cost and decreeing operating cost. But after a saddle point, the graph plotted between total cost and insulation thickness becomes a constant line that does not affect energy load. In this study, the optimum thickness has been calculated for the external wall through two methods: the DD method. The other is using the simulation method to check the point where insulation thickness is not economical. Calculations were repeated for all the five insulant materials used in the building for all cities in India. As insulation thickness increases, the material cost also increases. Thus, increasing the total cost, where the total cost is minimum, is the optimum thickness of the material as shown in Figures 3 and 4. The calculated value of optimum insulation thickness through the DD method is much higher than the simulated insulated thickness, as shown in Tables 7–12. The main cause of the change is that it only depends on *U* values and DD. It does not give whether the heat gain or loss is due to lights, solar, sky radiation, and people. The optimum value gain through DD method is calculated for the whole year and not applied for any schedule.

Table 7 Optimum insulation thickness with simulated and calculated in the presence of EPS

No.	*City*	X_{sim}	X_{cel}
1	Ahmedabad	68	68.6
2	Akola	100	152
3	Allahabad	68	64.86
4	Amritsar	61	74.84
5	Aurangabad	76	136.94
6	Barmer	64.5	70.33
7	Belgaum	70	98.3
8	Bengaluru	100	123.7
9	Bhagalpur	85	147.03
10	Bhopal	62	62.82
11	Bhubaneshwar	30	152.6
12	Bhuj	63	89
13	Bikaner	75	76.5
14	Chennai	100	164.11
15	Chitradurga	25	132.8
16	Dehradun	65	65.78
17	Dibrugarh	8	66.5
18	Gorakhpur	65	66.3
19	Guwahati	58	115
20	Gwalior	70	72
21	Hisar	70	75
22	Hyderabad	50	144.95
23	Imphal	51	65
24	Indore	35	58
25	Jabalpur	85	68
26	Jagdalpur	75	150
27	Jaipur	73	112
28	Jaisalmer	68	73
29	Jamnagar	32	60.34
30	Vishakhapatnam	53	87
31	Jodhpur	85	71.4
32	Jorhat	15	58.3
33	Kolkata	105	146.8
34	Kota	73	68.3
35	Kurnool	50	163
36	Lucknow	55	61
37	Mangalore	45	150
38	Mumbai	87	152

Table 7 Optimum insulation thickness with simulated and calculated in the presence of EPS (continued)

No.	*City*	X_{sim}	X_{cel}
39	Nagpur	79	157
40	Nellore	100	167
41	New Delhi	50	73
42	Panjim	100	150
43	Patna	60	64.3
44	Pune	65	122.3
45	Raipur	102	145
46	Rajkot	98	150
47	Ramagundam	88	164
48	Ranchi	45	58.2
49	Ratnagiri	55	73
50	Raxaul	45	65
51	Saharanpur	63	76.3
52	Shillong	55	67.3
53	Solapur	61	85
54	Srinagar	100	119
55	Surat	49	120
56	Tezpur	40	55
57	Thiruvananthapuram	65	120
58	Tiruchirappalli	58	176
59	Varanasi	53	75
60	Veraval	61	80

Table 8 Optimum insulation thickness with simulated and calculated in presence of XPS

No.	*City*	X_{sim}	X_{cel}
1	Ahmedabad	70	125
2	Akola	70	123.4
3	Allahabad	60	56.09
4	Amritsar	60	60.9
5	Aurangabad	62	111.09
6	Barmer	52	57.3
7	Belgaum	60	119.4
8	Bengaluru	70	100.56
9	Bhagalpur	80	123
10	Bhopal	50	52.3
11	Bhubaneshwar	30	80.3
12	Bhuj	58	92
13	Bikaner	60	62

Table 8 Optimum insulation thickness with simulated and calculated in presence of XPS (continued)

No.	*City*	X_{sim}	X_{cel}
14	Chennai	75	133.3
15	Chitradurga	25	108
16	Dehradun	51	51.8
17	Dibrugarh	9	54.2
18	Gorakhpur	50	54
19	Guwahati	65	120
20	Gwalior	25	58.6
21	Hisar	55	58.4
22	Hyderabad	71	118
23	Imphal	5	53
24	Indore	25	47
25	Jabalpur	100	150.8
26	Jagdalpur	112	170
27	Jaipur	88	55
28	Jaisalmer	83	57
29	Jamnagar	35	49.2
30	Vishakhapatnam	61	150
31	Jodhpur	65	58
32	Jorhat	20	100
33	Kolkata	100	119.3
34	Kota	55	56
35	Kurnool	47	132.3
36	Lucknow	42	50
37	Mangalore	61	122
38	Mumbai	58	124
39	Nagpur	78	120
40	Nellore	65	136
41	New Delhi	40	60
42	Panjim	85	95
43	Patna	49	52
44	Pune	53	99.4
45	Raipur	61	124
46	Rajkot	73	150
47	Ramagundam	89	133
48	Ranchi	40	42
49	Ratnagiri	78	125
50	Raxaul	50	53
51	Saharanpur	52	62

Table 8 Optimum insulation thickness with simulated and calculated in presence of XPS (continued)

No.	*City*	X_{sim}	X_{cel}
52	Shillong	64	87
53	Solapur	73	145
54	Srinagar	125	96.56
55	Surat	53	145
56	Tezpur	40	43
57	Thiruvananthapuram	63	89
58	Tiruchirappalli	67	143
59	Varanasi	45	57
60	Veraval	78	178

Table 9 Optimum insulation thickness with simulated and calculated in the presence of PUF

No.	*City*	X_{sim}	X_{cel}
1	Ahmedabad	65	64.3
2	Akola	80	142.2
3	Allahabad	65	64.54
4	Amritsar	58	70.1
5	Aurangabad	25	128
6	Barmer	48	65.89
7	Belgaum	89	137.7
8	Bengaluru	79	115.6
9	Bhagalpur	89	120
10	Bhopal	57	60
11	Bhubaneshwar	28	143
12	Bhuj	58	123
13	Bikaner	70	72
14	Chennai	30	154
15	Chitradurga	20	133
16	Dehradun	62	62
17	Dibrugarh	5	62.3
18	Gorakhpur	62	62.2
19	Guwahati	55	78
20	Gwalior	50	67.4
21	Hisar	63	73.13
22	Hyderabad	65	136
23	Imphal	8	61
24	Indore	50	54
25	Jabalpur	75	120
26	Jagdalpur	65	79

Table 9 Optimum insulation thickness with simulated and calculated in the presence of PUF (continued)

No.	*City*	X_{sim}	X_{cel}
27	Jaipur	55	63.5
28	Jaisalmer	62	65
29	Jamnagar	19	56
30	Vishakhapatnam	68	114
31	Jodhpur	50	66
32	Jorhat	10	50
33	Kolkata	65	35.3
34	Kota	100	64
35	Kurnool	37	153
36	Lucknow	38	90
37	Mangalore	40	140
38	Mumbai	78	142.4
39	Nagpur	63	91
40	Nellore	100	156.3
41	New Delhi	50	69
42	Panjim	50	52.3
43	Patna	49	60
44	Pune	55	114.5
45	Raipur	71	123
46	Rajkot	59	110
47	Ramagundam	89	153.4
48	Ranchi	50	50
49	Ratnagiri	51	79
50	Raxaul	48	68
51	Saharanpur	29	71
52	Shillong	45	100
53	Solapur	50	49
54	Srinagar	116	116
55	Surat	63	89
56	Tezpur	89	121
57	Thiruvananthapuram	73	165
58	Tiruchirappalli	55	112
59	Varanasi	54	65
60	Veraval	61	112

Table 10 Optimum insulation thickness with simulated and calculated in the presence of GW

No.	*City*	X_{sim}	X_{cel}
1	Ahmedabad	90	99.5
2	Akola	140	215.2
3	Allahabad	70	100
4	Amritsar	75	108.34
5	Aurangabad	41	194.3
6	Barmer	78	102.77
7	Belgaum	5	208.5
8	Bengaluru	100	176.2
9	Bhagalpur	65	121
10	Bhopal	45	90
11	Bhubaneshwar	46	216.3
12	Bhuj	61	98
13	Bikaner	100	111
14	Chennai	50	232.2
15	Chitradurga	40	189
16	Dehradun	95	95.7
17	Dibrugarh	7	97
18	Gorakhpur	50	97
19	Guwahati	58	125
20	Gwalior	63	104
21	Hisar	68	108.5
22	Hyderabad	69	205.6
23	Imphal	9	94.5
24	Indore	30	84.5
25	Jabalpur	95	125
26	Jagdalpur	115	189
27	Jaipur	91	98.6
28	Jaisalmer	60	101
29	Jamnagar	38	87
30	Vishakhapatnam	58	110
31	Jodhpur	85	102
32	Jorhat	35	80
33	Kolkata	125	208.25
34	Kota	110	99.3
35	Kurnool	75	230
36	Lucknow	78	90
37	Mangalore	68	201
38	Mumbai	68	178

Table 10 Optimum insulation thickness with simulated and calculated in the presence of GW (continued)

No.	*City*	X_{sim}	X_{cel}
39	Nagpur	56	89.8
40	Nellore	83	236
41	New Delhi	80	106
42	Panjim	87	125
43	Patna	70	94
44	Pune	49	174
45	Raipur	87	148
46	Rajkot	58	89
47	Ramagundam	87	232
48	Ranchi	61	80
49	Ratnagiri	41	98
50	Raxaul	48	85
51	Saharanpur	55	110
52	Shillong	36	152
53	Solapur	45	96
54	Srinagar	170	169.3
55	Surat	78	143
56	Tezpur	50	80
57	Thiruvananthapuram	67	151
58	Tiruchirappalli	59	250
59	Varanasi	73	100
60	Veraval	87	121

Table 11 Optimum insulation thickness with simulated and calculated in the presence of RW

No.	*City*	X_{sim}	X_{cel}
1	Ahmedabad	170	125
2	Akola	157	270
3	Allahabad	117	125.3
4	Amritsar	100	135.65
5	Aurangabad	50	243.3
6	Barmer	78	127.8
7	Belgaum	5	261.2
8	Bengaluru	85	220.7
9	Bhagalpur	59	128
10	Bhopal	75	112
11	Bhubaneshwar	60	271
12	Bhuj	89	178
13	Bikaner	78	138.5

Table 11 Optimum insulation thickness with simulated and calculated in the presence of RW (continued)

No.	*City*	X_{sim}	X_{cel}
14	Chennai	22	291
15	Chitradurga	22	154
16	Dehradun	50	61.6
17	Dibrugarh	10	121
18	Gorakhpur	50	121
19	Guwahati	58	98
20	Gwalior	68	131
21	Hisar	118	136
22	Hyderabad	85	258
23	Imphal	11	31.3
24	Indore	45	106
25	Jabalpur	100	159
26	Jagdalpur	125	201
27	Jaipur	100	189
28	Jaisalmer	55	135
29	Jamnagar	45	110
30	Vishakhapatnam	89	215
31	Jodhpur	95	130
32	Jorhat	37	100
33	Kolkata	112	261
34	Kota	120	124.3
35	Kurnool	79	290
36	Lucknow	87	112
37	Mangalore	65	267
38	Mumbai	78	270
39	Nagpur	69	198
40	Nellore	89	296
41	New Delhi	70	132.7
42	Panjim	100	189
43	Patna	100	117.3
44	Pune	81	218
45	Raipur	100	155
46	Rajkot	89	173
47	Ramagundam	120	291
48	Ranchi	51	99.8
49	Ratnagiri	87	129
50	Raxaul	54	100.3

Table 11 Optimum insulation thickness with simulated and calculated in the presence of RW (continued)

No.	*City*	X_{sim}	X_{cel}
51	Saharanpur	87	138
52	Shillong	98	190
53	Solapur	69	152
54	Srinagar	135	212
55	Surat	65	110
56	Tezpur	53	98.4
57	Thiruvananthapuram	112	187
58	Tiruchirappalli	125	312
59	Varanasi	87	127
60	Veraval	100	158

Table 7 to 11 shows the optimum insulation thickness for all selected insulation material corresponding to states. This insulation thickness is measured with both methods (DD and simulation) discussed above. GW and RW have the highest thickness compared to others. PUF material shows a good energy-saving performance, but it is not much economical and has the highest installation cost. PUF material is much expensive among them. EPS material is chosen for this study because it shows good performance when applied on external walls. EPS material shows a good energy saving of 45.8%. The optimum insulation thickness is calculated through the DD method by using equation (13). The simulated and calculated optimum thicknesses are presented in Table 12. Both calculations have no similarity. They both work in their own prospects. The optimum insulation thickness calculated through EnergyPlus software adds many parameters such as HVAC scheduling, occupancy schedule, wind velocity factor, solar and sky radiation, which are not considered in the optimum thickness calculations by DD method. Table 12 explains the payback period annual and annual energy saving per m^2 for all cities in India. This also shows that PUF has less payback period as compared to others. The maximum energy saving occurs in a cold place, i.e., required to control the heating load. The maximum energy saving occurs in Srinagar at approximately \$42.95/m^2.

6 Validation

Kurekci et al. (2016) also did a similar study using five different insulants in Turkey's climatic zones in their research. They also find out that GW and RW have the highest optimum thickness and PUF have the lowest thickness, as shown in Figure 4. Table 13 also concludes that PUF saves maximum energy in every city of India, i.e., almost 47.36% and GW. Ashok and Suman (2013) also came to the same conclusion using different insulation materials in the Indian environment and validated results through experimental study. They also investigate the effect of insulation material on energy load after applying on conventional walls.

Table 12 Saving and payback period for all cities in India

City	*EPS*			*XPS*			*PUF*			*GW*			*RW*		
	Saving sim (\$/m^2)	*$PP_{H,C}$ sim (yr.)*	*$PP_{H,C}$ cal (yr.)*	*AH,C sim (\$/m^2)*	*$PP_{H,C}$ sim (yr.)*	*$PP_{H,C}$ cal (yr.)*	*AH,C sim (\$/m^2)*	*$PP_{H,C}$ sim (yr.)*	*$PP_{H,C}$ cal (yr.)*	*AH,C sim (\$/m^2)*	*$PP_{H,C}$ sim (yr.)*	*$PP_{H,C}$ cal (yr.)*	*AH,C sim (\$/m^2)*	*$PP_{H,C}$ sim (yr.)*	*$PP_{H,C}$ cal (yr.)*
Ahmedabad	9.654	4.5	5.7	10.34	5.1	7.4	9.75	6.7	7.3	9.88	4.1	5.3	11.7	4.3	7.3
Akola	14.5	6.1	7.6	15.8	7.8	8.9	16.7	8.3	10.1	16.89	3.8	4.7	16.25	3.9	6.7
Allahabad	16.26	5.5	6.4	16.5	7.9	9.7	17.3	8.4	10.5	16.5	4.1	6.8	17.1	4.6	7.8
Amritsar	15.89	3.4	4.5	16.3	4.5	7.1	15.55	6.7	8.9	17.3	4.8	9.7	16.8	4.9	6.7
Aurangabad	7.08	4.2	5.9	7.09	6.1	8.9	7.12	8.4	10.8	7.55	5.1	8.5	6.05	5.5	8.7
Barmer	17.3	5.5	6.7	16.89	6.7	9.1	17.89	7.3	9.7	17.05	5.5	7.3	18.02	5.8	7.4
Belgaum	11.05	7.4	8.9	11.23	8.4	10.4	12.04	9.7	11.5	11.31	3.5	5.7	12.04	4.1	8.7
Bengaluru	36.3	6.1	8.3	37.3	7.4	9.7	39.49	8.9	10.7	38.8	4.8	6.8	39.5	5.1	9.7
Bhagalpur	18.35	4.5	5.7	18.04	5.9	8.9	19.04	6.2	9.7	17.65	3.4	6.8	18.65	4.5	7.4
Bhopal	6.6	3.8	4.9	6.6	4.7	9.4	6.58	5.9	9.5	7.28	3.9	8.2	7.08	4.2	7.7
Bhubaneshwar	9.87	4.8	5.7	12.1	5.7	9.4	12.07	6.3	8.9	10.73	4.1	9.7	11.11	4.5	7.8
Bhuj	15.5	5.9	6.7	16.04	6.7	10.2	15.89	8.4	11.7	16.78	4.5	9.9	16.01	4.7	7.9
Bikaner	18.9	4.8	6.9	19.17	5.2	9.7	19.21	7.3	10.4	20.69	5.4	9.8	22.01	5.6	8.7
Chennai	18.07	5.7	6.3	15.16	6.8	10.8	18.12	8.3	10.8	18.92	3.9	7.1	16.46	4.8	7.8
Chitradurga	6.3	6.9	9.1	6.27	8.1	11.4	6.8	9.7	11.4	6.6	4.5	8.8	6.45	4.9	7.9
Dehradun	4.9	4.1	5.9	5.22	5.7	9.7	6.9	6.4	8.7	7.3	4.3	8.9	8.5	4.7	7.6
Dibrugarh	11.5	8.1	9.9	12.78	10.4	12.7	11.8	11.4	13.4	11.05	3.5	8.7	12.07	3.9	6.7
Gorakhpur	14.05	6.9	8.7	14.6	7.9	10.8	14.26	10.7	11.8	13.8	3.8	8.9	14.02	4.1	7.8
Guwahati	18.8	8.6	10.7	17.89	9.5	11.7	19.05	11.7	13.8	18.08	4.5	9.8	18.8	4.7	7.9
Gwalior	20.81	6.7	9.1	22.8	7.4	11.9	22.6	8.3	10.4	21.9	3.5	8.7	22.05	4.2	6.7

Table 12 Saving and payback period for all cities in India (continued)

City	*EPS*			*XPS*			*PUF*			*GW*			*RW*		
	Saving sim (\$/m^2)	$PP_{H,C}$ *sim (yr.)*	$PP_{H,C}$ *cal (yr.)*	*AH,C sim* (\$/m^2)	$PP_{H,C}$ *sim (yr.)*	$PP_{H,C}$ *cal (yr.)*	*AH,C sim* (\$/m^2)	$PP_{H,C}$ *sim (yr.)*	$PP_{H,C}$ *cal (yr.)*	*AH,C sim* (\$/m^2)	$PP_{H,C}$ *sim (yr.)*	$PP_{H,C}$ *cal (yr.)*	*AH,C sim* (\$/m^2)	$PP_{H,C}$ *sim (yr.)*	$PP_{H,C}$ *cal (yr.)*
Hisar	17.5	7.1	10.4	17.2	8.9	12.4	17.43	9.3	11.5	16.4	4.1	9.1	16.5	4.9	7.7
Hyderabad	15.8	5.9	8.4	15.1	6.4	9.7	15.11	7.4	10.4	15.06	4.8	9.5	14.97	3.9	6.3
Imphal	20.2	7.6	11.6	21.78	9.4	11.4	22.01	11.8	13.4	21.14	3.5	8.5	22.09	3.7	5.5
Indore	4.7	6.4	9.7	4.6	7.4	10.8	4.69	9.4	11.2	4.65	4.2	9.1	4.63	4.7	7.1
Jabalpur	15.09	5.1	7.9	15.7	6.9	9.7	15.2	8.9	10.7	14.8	4.5	9.5	14.64	4.8	7.2
Jagdalpur	11.56	5.4	8.3	11.69	7.3	10.3	11.59	10.4	12.4	12.03	4.8	7.8	11.4	5.2	8.5
Jaipur	18.68	6.4	7.4	18.95	7.8	10.7	18.76	11.3	13.7	17.89	5.5	8.9	18.18	5.7	8.7
Jaisalmer	23.76	4.7	8.4	24.2	5.9	9.8	23.14	8.9	10.9	23.95	4.3	8.7	23.46	5.9	8.9
Jamnagar	17.89	4.9	8.9	17.3	6.3	10.4	18.1	8.4	10.5	17.54	5.6	9.1	18.3	6.8	9.1
Jodhpur	16.4	3.7	5.4	16.96	4.7	9.7	16.48	5.9	8.9	16.59	5.1	7.2	16.8	5.5	7.8
Jorhat	17.9	6.1	8.9	18.3	7.4	11.8	18.69	10.4	12.5	17.56	4.5	7.8	18.01	5.1	7.1
Kolkata	15.93	8.1	11.4	15.6	9.8	12.4	16.01	11.5	13.8	15.53	4.3	7.9	15.71	5.7	7.7
Kota	14.3	7.2	10.8	13.76	8.4	12.7	14.13	10.2	12.8	14.01	4.8	8.7	14.52	5.9	7.9
Kurnool	25.3	4.9	9.7	25.8	5.4	9.8	25.46	6.4	9.4	25.6	4.7	8.9	25.01	5.2	7.2
Lucknow	15.8	7.1	11.6	16.78	8.7	11.4	15.01	10.2	13.4	16.8	5.5	9.7	16.78	5.7	7.5
Mangalore	11.4	5.4	10.4	11.57	6.9	10.7	11.44	8.3	10.5	11.2	3.5	8.4	12.3	4.7	7.3
Mumbai	22.8	4.7	8.9	21.53	5.8	9.6	21.3	8.4	12.3	22.87	4.8	9.3	21.9	4.9	7.5
Nagpur	17.8	6.2	10.4	18.12	7.3	11.7	17.9	9.4	11.5	18.00	4.3	9.7	17.63	5.1	8.1
Nellore	11.75	7.1	11.8	11.06	9.4	11.7	10.64	10.7	12.8	15.5	4.9	9.9	10.2	5.5	8.5
New Delhi	10.25	6.3	9.7	10.525	7.1	10.7	11.87	11.1	13.7	10.71	5.2	10.1	12.03	6.1	9.4

Table 12 Saving and payback period for all cities in India (continued)

City	*EPS*			*XPS*			*PUF*			*GW*			*RW*		
	Saving sim (\$/m²)	$PP_{H,C}$ *sim (yr.)*	$PP_{H,C}$ *cal (yr.)*	*AH,C sim (\$/m²)*	$PP_{H,C}$ *sim (yr.)*	$PP_{H,C}$ *cal (yr.)*	*AH,C sim (\$/m²)*	$PP_{H,C}$ *sim (yr.)*	$PP_{H,C}$ *cal (yr.)*	*AH,C sim (\$/m²)*	$PP_{H,C}$ *sim (yr.)*	$PP_{H,C}$ *cal (yr.)*	*AH,C sim (\$/m²)*	$PP_{H,C}$ *sim (yr.)*	$PP_{H,C}$ *cal (yr.)*
Panjim	12.05	4.5	8.7	12.61	5.6	97	13.07	8.3	10.8	12.14	4.5	10.2	13.4	5.1	8.1
Patna	13.04	5.7	9.1	14.56	6.2	10.7	14.78	8.7	10.8	13.08	4.4	10.5	13.98	4.9	7.3
Pune	14.07	7.1	10.4	13.5	8.3	11.4	14.87	10.3	12.7	14.56	3.5	7.4	13.45	3.8	6.3
Raipur	18.8	5.4	8.7	18.05	6.4	10.7	19.78	9.4	11.5	18.46	4.3	8.4	17.56	3.7	6.1
Rajkot	21.02	4.7	10.5	22.78	5.2	9.8	23.81	8.4	12.2	20.98	5.2	9.7	21.34	4.7	7.2
Ramagundam	15.89	7.4	11.9	14.21	8.3	11.7	15.91	10.4	13.7	14.01	5.5	9.1	14.45	5.1	8.3
Ranchi	17.21	6.7	9.3	18.56	7.2	10.4	16.3	9.7	11.5	18.98	5.7	9.7	17.5	5.7	8.5
Ratnagiri	18.8	5.9	10.4	19.54	6.3	11.7	18.56	8.9	10.5	19.21	4.7	8.7	18.71	3.9	6.4
Raxaul	21.87	4.9	8.9	22.14	5.4	9.8	21.98	8.1	10.1	22.34	3.8	6.9	21.54	4.8	7.2
Saharanpur	28.1	6.7	10.4	27.56	7.4	10.7	28.31	9.8	11.5	27.14	4.8	7.3	27.54	5.2	8.3
Shillong	19.56	4.7	7.8	20.14	5.2	9.8	22.56	7.4	10.3	20.13	3.1	4.8	20.36	4.7	7.4
Solapur	22.35	6.8	9.7	24.36	7.3	10.7	23.51	9.7	12.5	22.14	3.4	5.4	21.98	4.2	7.1
Srinagar	42.95	4.9	7.1	45.56	5.8	9.8	43.44	8.3	10.8	47.5	2.2	3.9	43.25	3.1	6.7
Surat	18.01	5.4	8.7	19.56	6.1	9.9	18.87	8.4	10.9	17.56	5.5	10.4	18.13	6.1	9.2
Tezpur	21.22	6.7	11.4	21.98	7.4	10.3	22.14	9.7	11.5	21.56	4.5	8.7	20.78	5.1	8.4
Tiruchirappalli	11.56	8.1	10.4	12.07	9.5	12.4	11.71	11.4	13.8	10.99	5.8	9.7	11.98	5.9	8.9
Varanasi	18.8	9.6	12.7	19.87	10.4	13.7	20.81	11.9	13.5	19.10	5.5	9.9	19.71	4.7	7.4
Veraval	22.69	7.4	10.4	21.59	8.3	10.7	23.14	10.8	12.8	22.14	3.9	5.7	21.94	4.2	7.1
Vishakhapatnam	24.98	5.4	6.8	23.17	6.7	8.3	24.91	8.3	11.2	20.89	4.7	8.7	21.57	3.8	6.5
Thiruvananthapuram	19.68	4.8	6.1	20.59	5.8	8.9	21.59	6.7	10.4	18.98	5.8	6.8	18.12	4.8	7.8

Figure 3 Calculated total cost of five different states under diff. insulation thickness (see online version for colours)

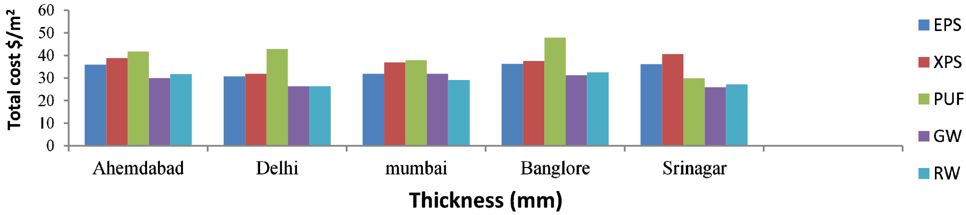


Figure 4 Simulated total cost of five different states under diff. insulation thickness (see online version for colours)

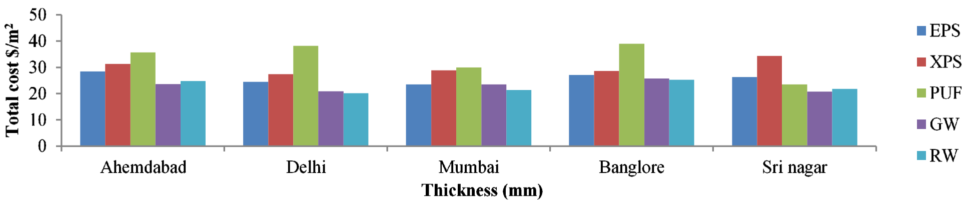


Figure 5 The optimum thickness for the external wall under different DD (see online version for colours)

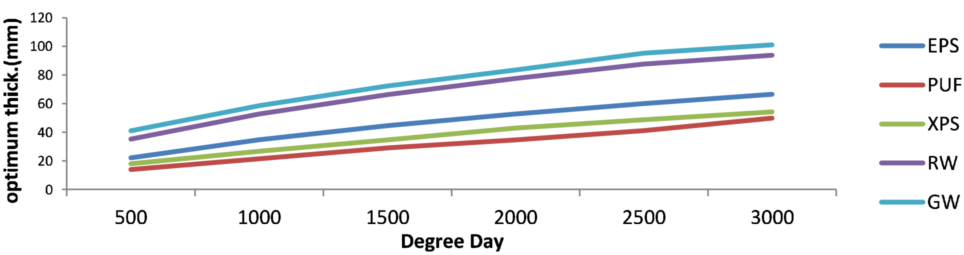


Table 13 Energy saving for simulated insulation material and calculated insulation material

	EPS		*XPS*		*PUF*		*GW*		*RW*	
	Sim	*Cal*	*Sim*	*Cal*	*Sim*	*Cal*	*Sim*	*Cal*	*Sim*	*Cal*
Heating	58.3	60.69	58.8	62.8	68.3	75.4	48.8	51.2	51.3	59.4
Cooling	6.89	7.3	7.1	8.93	8.4	10.3	5.7	6.36	5.98	6.78
Total	45.8	49.3	44.98	45.89	47.36	50.98	38.89	40.23	39.32	41.57

7 Novelty of work

The protection of the environment is directly related to energy use. When we consume less power, the amount of toxic fumes released by industries, construction sites, buildings, etc. are reduced. Thus, by conserving the earth's natural resources we can safeguard the ecosystems from destruction. Cutting back on energy consumption reduces the amount of electricity that power plants have to make, subsequently reducing the amount of fossil fuels that are burned each day. Thermal insulation is an essential parameter in the building sector to save energy and money. This research focuses on using five insulation materials (extruded polystyrene, expanded polystyrene, glass wool, rock wool, and polyurethane). It investigates the effect of the insulation material's thermos-physical properties in terms of saving energy, life cycle cost, and payback period. Energy savings are calculated for the cities indicated as most similar by each method. The difference in energy efficiency savings between these two methods is analysed to determine the potential error of each method. Thus, this work is contributing towards a solution of saving energy to safeguard the environment.

8 Conclusions

As the natural sources of energy are limited on our continent, thus the focus on energy conversation is the foremost need of the hour. The efficient use of products, particularly in the building sector, where unlimited energy consumption takes place, needs to be rectified.

This study compared both the DD method and simulation technique for different climatic zones of India's subcontinent. Both methods have a significant contribution to the energy-saving sector. The calculation is based on using five different types of insulation materials applied to buildings in 60 cities of India in different climatic zones. Chennai has the highest HDD of 3,997 and also the lowest CDD of 0. However, 0 is recorded in some other cities also. As DD increases, the optimum insulation thickness simultaneously increases, and the operating cost decreases. Both the calculations show the same thickness pattern: PUF has the thinnest thickness among them for the same region. The insulation material is not much affected by hot areas' heat, but good performance is observed in cool locations. GW and RW have the highest thickness compared to others. PUF material shows a good energy-saving performance, but it is not much economical and has the highest installation cost. PUF material is much expensive among them. EPS material is chosen for this study because it shows good performance when applied on external walls. EPS material shows a good energy saving of 45.8%.

The optimum insulation thickness calculated through EnergyPlus software adds many parameters such as HVAC scheduling, occupancy schedule, wind velocity factor, solar and sky radiation, which are not considered in the optimum thickness calculations by DD method. It shows that PUF has less payback period as compared to others. The maximum energy saving occurs in a cold place, i.e., required to control the heating load. The maximum energy saving occurs in Srinagar at approximately $42.95/m^2. EnergyPlus gives a detailed explanation of the annual payback period and annual energy saving per m^2 for all the Indian cities studied.

Net saving, life cycle cost, and the payback period are directly dependent on a selection of insulation material, i.e., when applied insulant material in the building is expensive, it directly influences the building's installation cost and decreases the operating cost. Thus, by applying the economical insulation material, the building owner gets optimum results.

It is suggested that future analysis can be done by also investigating the effect of building type and ways to improve the HDD/CDD method through a more rigorous analysis of the relevant variables.

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