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ORIGINAL PAPER

Optimum level of insulation for energy efficient envelope of office buildings

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Abstract Building envelope plays an important role in energy efficiency of the buildings as it is the only permanent source of energy efficiency. A well-designed building envelope reduces the demand of HVAC and lighting load. When insulation is provided in the building envelope, it further enhances the energy efficiency. Therefore, it is important to create thermal resistant building envelope considering both the energy consumption and the associated costs. Thermal insulation has a considerable positive effect on reducing the heating and cooling energy demand. It is seen from the tests conducted by Nasrollahi and Nooraei (2013) for design of energy efficient and cost-effective office buildings that initial increase in insulation reduces the heating/cooling load but beyond a certain limit, there is no substantial effect of reduction in heating/cooling load with increase in insulation indicating that there is an optimum value beyond which insulation has no substantial effect on reduction in heating/cooling load. Therefore, the paper attempts to find out this optimum level of insulation so that the building envelope is cost-effective and energy efficient. Three case studies of energy efficient LEED (Leadership in Energy and Environmental Design)/GRIHA (Green Rating for Integrated Habitat Assessment) certified buildings have been considered to determine the optimum level of insulation. In the analysis, comparison has been made between *U*-values of various components of the building envelopes of three case studies with the *U*-values prescribed by Energy Conservation Building Code (ECBC)-2007 for various components of the building envelopes based on daytime or 24-h usage, and location of the buildings in composite/warm and humid climate zones. Thereafter, results obtained from the analysis have been compared with the optimum *U*-values derived from the tests conducted by Nasrollahi and Nooraei (2013) to arrive at the optimum level of insulation. The optimum level of insulation has been found to be 30% above *U*-values prescribed by Energy Conservation Building Code.

Keywords Building envelope · Envelope performance factor · Insulation · *U*-value · Efficiency

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Introduction

Indian Green Building Council (IGBC) and Green Rating for Integrated Habitat Assessment council (GRIHA) are the agencies to rate green buildings in India. While LEED (Leadership in Energy and Environmental Design) buildings are certified by IGBC as "certified", "silver", "gold", and platinum with platinum as highest rating, GRIHA council rates them as one star to five stars with five stars being highest rating. Score to be achieved in LEED certification is 40–49 for "certified", 50–59 for "silver", 60–79 for "gold" and 80–100 for "platinum" rating. Score to be achieved in GRIHA rating is 50–60 for one-star, 61–70 for two-star, 71–80 for three-star, 81–90 for four-star and 91–100 for five-star rating. The buildings are rated based on various mandatory, obligatory and optional parameters which include sustainable site planning, energy efficiency, water efficiency, indoor air quality, use of green materials and innovative design, energy efficiency being the important criterion. Though the energy efficiency can be achieved through use of energy efficient materials, lighting and HVAC (heating, ventilation and air conditioning system), building envelope has an important role in making cost-effective energy efficient buildings.

Energy efficient building envelope reduces energy demand for HVAC and lighting. Envelope is critical in case of office buildings as they require more illuminated indoor space provided through additional glass area compared to residential, institutional and industrial buildings. To make the building envelope energy efficient, insulation needs to be provided in various components of the buildings. In the present study, three green-rated office buildings having energy efficient envelopes have been considered to determine the optimum level of insulation for energy efficiency.

Present study was conducted at Delhi in July 2014 in partial fulfilment of degree of MA in public policy and sustainable development. Energy efficiency of the buildings has been calculated from envelope performance factor (EPF) and heat gain method in all three case studies. The aim of the study is to find out the optimum level of insulation to make the building envelope, cost-effective and energy efficient.

Literature review

The study conducted by Nasrollahi and Nooraei (2013) for design of energy efficient and cost-effective office buildings highlights the importance of creating thermal resistant building envelope and performing an analysis in consideration of both the energy consumption and the associated costs. Study concludes that thermal insulation has a considerable positive effect on reducing the heating demand, however, has a negative effect on increasing the cooling energy demand as a result of greater insulated areas in the envelope.

As per the report established by Ecofys for European insulation manufacturers association published by Boermans and Petersdorff (2007), in residential buildings of Southern Europe, thermal insulation also reduces the energy demand for cooling. In particular, roof and wall, insulation provides very robust and considerable savings. A well-balanced package of floor, wall and roof insulation, combined with proper shading and a good ventilation strategy, results in a significant and cost-effective reduction in the energy demand for heating and cooling. This effect can be generalized for all residential buildings with reasonable passive cooling strategies and is quite robust in relation to "non designed behaviour" of tenants, or in case of a lower mass building. Kneifel (2010) concludes that conventional energy efficiency measures can be used to reduce energy use by 20–30% on average without any significant alterations to the building design. In a case study of the Main Hall, Shinawatra University, Praditsmanont and Chungpaibulpatana (2008), it was observed that the increased investment cost of the Main Hall envelope requires a discounted payback period of only 3–5 years, depending on envelope types used in the comparison. Furthermore, it should be noted that greater saving and more favourable payback period could be obtained if this highly energy efficient envelope is applied to other typical buildings, especially high rise structures in urban areas.

Newsham et al. (2009) have concluded that on average, LEED buildings used 18–39% less energy per floor area than their conventional counterparts; however, 28–35% of LEED buildings use more energy than their conventional counterparts. Andradottir (1998) provided an introduction to simulation optimization, with emphasis on gradient-based techniques for continuous parameter simulation optimization and on random search methods for discrete parameter simulation optimization. Jay April et al. (2003) summarized some of the most relevant approaches that have been developed for the purpose of optimizing simulated systems and concentrated on the metaheuristic black-box approach that leads the field of practical applications and provide some relevant details of implementation of the approach in commercial software.

Researchers at the National Renewable Energy Laboratory have brought out several papers based on whole building energy simulations of energy efficient building designs. Torcellini et al. (2006) analysed existing high-performance commercial buildings and found that current technology can substantially change how buildings perform by decreasing energy use by 25–70% lower than code, which can be realized through a whole building analysis approach. Griffith et al. (2007) simulated the potential for net zero energy commercial buildings in the USA and found that with current technologies and design practices, 62% of buildings and 47% of floor space could reach net zero energy use. Further, improving the building envelope, lighting controls, plug and process loads and HVAC system to the best currently available technologies would reduce energy use by 43% below ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) 90.1-2004 compliant design. Griffith et al. (2008) developed a methodology for analysing the energy performance of commercial buildings and examined for its ability to represent the entire sector. They developed a methodology for modelling commercial buildings energy performance by simulating the US building stock and determined that a set of building types and locations is required to effectively represent the building stock and weather, building design, and energy loads lead to a large variation in total site energy use.

ASHRAE (2008) has recently introduced "ASHRAE Advanced Energy Design Guides" for several building types, which give recommendations on how to build a minimum of 30% better than ASHRAE 90.1-1999 based on the use of conventional technologies and design approaches, and vary with climate zones.

Cetiner and Ozkan (2005) simulated different glass façade designs and found that the most energy efficient double skin glass facade is about 22.84% more efficient than the most energy efficient single skin glass facade. Additionally, the most cost-efficient single glass facade is about 24.68% more efficient than the most cost-efficient double glass facade.

As per Lippiatt (2007), BEES (Building for Environmental and Economic Sustainability) version 4.0 software implements a rational, systematic technique for selecting environmentally preferred, cost-effective building products.

As per Nasrollahi and Nooraei (2013), the cooling energy demand of the new generation office building is decreased by reducing the external heat gains through an optimum orientation and building form, an optimized window area as well as the application of shading devices. Because it is not possible to completely prevent external heat gains and also there are considerable internal heat gains, the building must be cooled. Natural ventilation is an effective measure to reduce the cooling energy demand and cross-ventilation is much more effective than single side ventilation. There is a significant difference between the naturally ventilated and the fully air-conditioned buildings in terms of thermal insulation. Natural ventilation minimizes the negative effects of insulation on the thermal behaviour of the building during summer, which, in turn, allows a better insulated envelope to reduce the heating demand in winter. In fully air-conditioned buildings, where the windows are always closed, good thermal insulation leads to a greater increase in the cooling demand though reduces heating demand as the heat is trapped inside and cannot be dissipated to the outdoor air, which results in a warmer interior and a greater need for cooling. As per International Energy Agency (2013), building envelope improvements can lead to occupant comfort and the quality of life to millions of citizens, while offering significant non-energy benefits such as reduced healthcare costs and reduced mortality of "at risk" populations.

Energy efficiency in buildings can be achieved by applying various codal provisions in planning, design and construction of new buildings. In existing buildings, retrofitting may be essential to make them energy efficient. As per Sandansamy et al. (2013), it is necessary that energy efficiency of various commercial and public buildings in India is assessed and wherever necessary energy retrofit be carried out, so that India is able to avoid huge energy deficits/energy starvation in the coming decades.

The building envelope consisting of walls, roof and fenestration system forms the primary thermal barrier between interior and exterior and plays a key role in providing comfort, natural lighting and ventilation which determine energy requirement for heating and cooling of the building. Thus, energy efficient building envelope is to be provided with cost-effective energy efficient integrated facade system that optimizes daylight while minimizing energy requirements for heating and cooling through external shading, proper orientation and dynamic solar controls enhanced with optimum insulation provided in the components of the building envelope.

Materials and methods

Base case

Each building design is the base case for that particular building. Thus, to make the base case energy efficient, it is important to design the building considering the climatic conditions with the following parameters:

- Orientation and shape of the building for desired sun heat and sun light.
- Window-to-wall ratio (WWR) for optimum daylight and ventilation.
- Windows/glazing design for increasing daylight and reducing the need for artificial lighting.
- Provision of balconies, verandas, courtyards, wind towers, skylights and other openings for cross-ventilation.
- Provision of shading devices and landscape to allow the desirable sun and cut off the non-desirable sun as well as to divert the wind flow wherever required.

Energy efficiency can be further improved by designing components of the building envelope energy efficient by adopting appropriate U-value through insulation, cavity walls, reflective coatings on roof, reflective glass on facade, etc.

Case studies

In the present study, three green-rated energy efficient buildings are considered as follows:

- Case study I: Jawaharlal Nehru Bhawan Delhi, located in composite climate zone and LEED "gold" rated. The building has cavity walls filled with glass wool, over deck polyurethane (PU) insulation, brick coba water proofing treatment with broken china tiles on rooftop and solar reflective double glazed units (DGU) in fenestration with WWR as 27.6%.
- Case study II: Indira Paryavaran Bhawan, Delhi, located in composite climate zone and LEED "platinum" and 5 stars rated by GRIHA council. The building has autoclaved aerated concrete (AAC) blocks in outer walls, rock wool insulation in cavity walls, fly ash lime and gypsum (FAL-G) bricks in inner walls, brick coba treatment with PU insulation and solar reflective tiles on roof and low-e double glazed units in fenestration with WWR as 21.8%.
- Case study III: Office Building for BG Mumbai, located in warm and humid climate zone and LEED "gold" rated. The building has cavity walls, over deck PU insulation and brick coba treatment with solar reflective tiles on rooftop and low-e double glazed units in fenestration with WWR as 20.6%.

Each case study has been analysed considering the following four conditions:

Condition I: *Base case condition* in which *U*-values of wall assembly, roof assembly and fenestration have been considered as 1.87, 1.81 and 2.7 W per square metre per degree celsius (W/m^2 °C), respectively, and solar heat gain coefficient (SHGC) for fenestration as 0.7.

Condition II: *ECBC 2007 compliant condition* in which *U*-values prescribed by ECBC for wall assembly, roof assembly and fenestration for the climate zone of the case study have been considered as 0.44, 0.409 and 3.3 W/m^2 °C, respectively, with SHGC for fenestration as 2.5 as ECBC prescribes same *U*-value and SHGC for both (composite, and warm and humid) the climate zones.

Condition III: *Actual building condition*, in which actual *U*-values are considered for wall assembly, roof assembly and fenestration as 0.428, 0.38, and 2.8 W/m^2 °C, respectively, for case study I, 0.37, 0.26 and 1.5 W/m^2 °C for case study II and 0.52, 0.91 and 1.5 W/m^2 °C for case study III and actual SHGC of the fenestration as 0.41 for case study I, 0.32 and 0.25 for case study II as per the provisions of without shading and with shading, respectively, and 0.32 for case study III.

Condition IV: *High-performance glass condition* in which lower *U*-value and SHGC of glass have been used compared to condition III. *U*-values and SHGC used for fenestration are 1.6 W/m^2 °C and 0.18 for case study I, 1.5 W/m^2 °C and 0.20 for case study II, 1.5 W/m^2 °C and 0.20 for case study III, respectively.

In all the above conditions, areas of wall, roof, and fenestration remain same for respective buildings.

Method

Energy efficiency has been calculated by EPF and heat gain coefficient method in each building for all the above-mentioned four conditions. EPF coefficients have been taken from ECBC user guide 2009 for composite climate and daytime occupancy for case study I and II as 6.01 for walls, 11.93 for roofs, −1.75 for North windows, −1.25 for non-North windows and for warm and humid climate and daytime occupancy for case study III as 6.42 for walls, 9.86 for roofs, −1.58 for North windows, −1.00 for non-North windows. SHGC for North windows is 40.65 and for non-North windows 54.51 for case study I and II, and 34.95 for North windows and 43.09 for non-North windows for case study III.

In method 1, energy efficiency is calculated using trade-off method given in ECBC user guide 2009 and in method 2, by heat gain method inside the building using solar incidence values taken from charts generated from weather file of Delhi and Mumbai in ECOTECT software. Peak values of average solar incidence for facade are taken from ECOTECT for Delhi as 732 in East, 307 in West, 98 in North and 661 in South direction and for roof as 776, while the values for Mumbai have been taken as 648 in East, 186 in West, 53 in North and 604 in South and 614 for roof. Average temperature difference during the day has been considered as 10 °C and during the night as 5 °C.

Analysis of method 1

Building envelope trade-off method has been adopted for working out the energy efficiency in conditions I to IV, and EPF is calculated using the following equation given in ECBC user guide 2009;

$$EPF_{Total} = EPF_{Roof} + EPF_{Wall} + EPF_{Fenest}$$

where

$$\mathrm{EPF}_{\mathrm{Roof}} = C_{\mathrm{Roof}} \sum_{s=1}^{n} U_s A_s$$

$$\mathrm{EPF}_{\mathrm{Wall}} = C_{\mathrm{Wall,}}\mathrm{Mass} \sum_{s=1}^{n} U_s A_s + C_{\mathrm{Wall,}}\ \mathrm{Other} \sum_{s=1}^{n} U_s A_s$$

$$\mathrm{EPF}_{\mathrm{Fenest}} = C_{1\mathrm{Fenest,}}\mathrm{North} \sum_{w=1}^{n} \mathrm{SHGC}_w M_w A_w$$

$$+ C_{2\mathrm{Fenest,}}\mathrm{North} \sum_{w=1}^{n} U_w A_w +$$

$$C_{1\mathrm{Fenest,}}\mathrm{Non\ North} \sum_{w=1}^{n} \mathrm{SHGC}_w M_w A_w$$

$$+ C_{2\mathrm{Fenest,}}\mathrm{Non\ North} \sum_{w=1}^{n} U_w A_w +$$

$$C_{1\mathrm{Fenest,}}\mathrm{Skylight} \sum_{s=1}^{n} \mathrm{SHGC}_s A_s M_s + C_{2\mathrm{Fenest,}}\mathrm{Skylight} \sum_{s=1}^{n} U_s A_s$$

where $\mathrm{EPF}_{\mathrm{Total}}$, $\mathrm{EPF}_{\mathrm{Roof}}$, $\mathrm{EPF}_{\mathrm{Wall}}$ and $\mathrm{EPF}_{\mathrm{Fenest}}$ denote envelope performance factor (EPF) for envelope, roof, wall and fenestration, respectively. A_s is the area of a specific envelope component referenced by subscript "s" or for window the subscript "w". C_{Roof}, C_{Wall}, $C_{1\mathrm{Fenest}}$, and $C_{2\mathrm{Fenest}}$ are the envelope performance factor coefficient for the roof, wall, fenestration 1 and fenestration 2, respectively. M_w is a multiplier for the window SHGC that depends up on the projection factor of an overhang or side fin. U_s is the U-value for the envelope component referred by the subscript "s". SHGC_w and SHGC_s are solar heat gain coefficients for windows and skylight, respectively.

Analysis of method 2

Heat gain inside the building has been calculated by using solar incidence values (mentioned above in Method) taken from weather file in ECOTECT using the following formula:

Net heat gain inside the building = Heat gain through fenestration + Heat gain through wall + Heat gain through roof.
Heat gain through fenestration =
=Solar factor × solar incidence × fenestration area + ΔT × U value of fenestration × fenestration area. Heat gain through wall
=Solar factor × solar incidence × wall area + ΔT × U value of wall × wall area Heat gain through roof
=Solar factor × solar incidence × roof area + ΔT × U value of roof × roof area

Results and discussion

Energy efficiency of the case studies under different conditions

Results of case studies I, II and III in terms of efficiency derived from method 1 and 2 are given in Tables 1, 2, 3 and 4 as under;

Results of case study III are obtained by method 2 only.

The following observations are made from Tables 1, 2, 3 and 4;

i. In both the methods as evident from Tables 1 and 2, lower the U-value, better is the energy efficiency.
ii. From Table 4, it is observed that under ECBC compliant conditions, for same U-values, heat input is different in all the cases showing that the design of the building plays a vital role in energy efficiency. It is further observed from the present study also, building envelope of U-values prescribed by ECBC leads to higher energy efficiency over the base case.
iii. When U-value/SHGC is lowered by providing high-performance glass, energy efficiency increases in all the case studies as observed in condition IV in Tables 1, 2 and 3.
iv. Low-e glass provides higher energy efficiency than solar reflective DGU as observed in Table 2.

Table 1 Case study I

	Condition I	Condition II	Condition III	Condition IV
Method 1				
EPF	431631	111165	131668	102021
Efficiency	Base case	74.25%	69.49%	76.36%
Method 2				
Amount of heat input in watts	544250	212840	241826	145504
Percentage of heat input in watts	100%	40.6%	46.13%	27.75%
Efficiency	Base case	59.4%	53.7%	72.25%

Table 2 Case study II

	Condition I	Condition II	Condition III	Condition IV
Method 1				
EPF	226671	55481	55003	42737
Efficiency	Base case	75.52%	75.73%	81.1%
Method 2				
Amount of heat input in watts	230850	107252	88857	66236
Percentage of heat input in watts	100%	46.46%	38.49%	28.69%
Efficiency	Base case	53.54%	61.51%	71.31%

Table 3 Case study III

	Condition I	Condition II	Condition III	Condition IV
Method 2				
Amount of heat input in watts	101120	40705	43124	33833
Percentage of heat input in watts	100%	40.25%	42.65%	33.46%
Efficiency	Base case	59.75%	57.35%	66.54%

Results of energy efficiency of all the three case studies (Tables 1, 2 and 3) are summarized in Table 4

Table 4 Envelope efficiency of case studies

Condition	Envelope efficiency					
	Case study I		Case study II		Case study III	
	Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
Conventional	Base case	Base case	Base case	Base case	–	Base case
ECBC compliant	74.25%	59.4%	75.52%	53.54%	–	59.75%
Actual building	69.49%	53.7%	75.73%	61.51%	–	57.35%
High-performance glass condition	76.36%	72.25%	81.1%	71.31%	–	66.54%

Optimum level of insulation with respect to ECBC

Nasrollahi and Nooraei (2013) conducted four sets of parametric tests to estimate the potential energy savings of additional thermal insulation in office constructions based on the main objectives of energy efficiency and cost efficiency for the new generation office buildings. In these tests, the heating and cooling demand was extracted from the simulation results in each test for the entire year on hourly basis using EDSL TAS version 9.2.1 tutorial 2011. Simulation was done for 9 envelopes using different *U*-values in each case. Out of the 9 envelopes, envelope 1 was for typical construction, envelope 2 as per provisions of code and envelopes 3–9 in the sequence of reduced mean *U*-values with envelope 3 as the maximum mean *U*-value and envelope 9 as the minimum mean *U*-value. In Tests 1 and 3, building was naturally ventilated, and in Tests 2 and 4, centrally air-conditioned. In Tests 1 and 2, windows were double glazed and in Tests 3 and 4, with low-e double glazed. Therefore, *U*-values of window glass and frames in Tests 1 and 2 were different from the *U*-values of Test 3 and 4 for all the 9 envelopes.

Since Tests 2 and 4 relate to centrally air-conditioned buildings and buildings taken up for the case studies are also centrally air-conditioned, these tests were considered for the comparison with results obtained from the present

Table 5 Test 2 conducted by Nasrollahi and Nooraei (2013)

Envelope	Mean *U*-value (W/m^2 °C)	Heating load (kW h/m^2a)	Cooling load (kW h/m^2a)	Total load (kW h/m^2a)
1	2.85	23.9	25.4	49.3
2	2.66	20.9	25.7	46.6
3	2.13	13.0	30.8	43.8
4	**2.01**	**11.4**	**31.7**	**43.1**
5	1.46	8.9	34.3	43.2
6	1.24	7.8	35.9	43.7
7	1.05	6.7	37.6	44.3
8	0.96	6.3	38.6	44.9
9	0.80	5.8	41.1	46.9

Table 6 Test 4 conducted by Nasrollahi and Nooraei (2013)

Envelope	Mean *U*-value (W/m^2 °C)	Heating load (kW h/m^2a)	Cooling load (kW h/m^2a)	Total load (kW h/m^2a)
3	1.82	11.9	18.4	30.3
4	1.71	10.3	18.5	28.8
5	1.15	7.7	19.4	27.1
6	0.93	6.6	20.0	26.6
7	**0.74**	**5.5**	**20.7**	**26.2**
8	0.65	5.1	21.1	26.2
9	0.48	4.5	22.8	27.3

study. Heating, cooling and total load in kilo watt hours per square metre per annum (kW h/m^2a) of the simulated cases of Test 2 and 4 conducted by Nasrollahi and Nooraei (2013) are given in Tables 5 and 6 for various envelopes and mean *U*-values;

The results of Tests 2 and 4 have been studied in the context of composite climate of case studies I and II of Delhi in which heating and cooling loads are equally important due to extreme winter and summer. Therefore, optimum total load has been considered for determining the optimum level of insulation. In case of warm and humid climate of case study III, though cooling load is important, optimum total load has been considered in this case also as ECBC prescribes same *U*-values for both the climate zones.

In Test 2, window glazing has been provided with DGU having *U*-values for window glazing as 2.86 and frame as 2.85 W/m^2 °C, and in Test 4, glazing material has been replaced by low- e DGU with *U*- values for window glazing as 1.29 and frame as 2.34 W/m^2 °C. It is observed from Test 2 in Table 5 that heating load decreases by 76% while cooling load increases by 62% with mean *U*-values decreasing by 72% from envelope 1–9. It is also observed that total energy demand from heating and cooling is optimum in envelope 4 with mean *U*-value of 2.01 W/ m^2 °C beyond which it further starts increasing indicating this mean *U*-value as optimum level of insulation for Test 2.

In Test 4 keeping *U*-values of wall and roof same as Test 2, glass has been replaced with low-e glass of 170% more solar absorption and 20% less solar transmittance. The results show 62% reduction in heating load while 24% increase in cooling load from envelope 3–9. It is also observed that total energy demand from heating and cooling is optimum in envelope 7 with mean *U*-value of 0.74 W/m^2 °C beyond which it further starts increasing indicating this mean *U*-value as optimum level of insulation for Test 4.

From Test 2, it is observed that optimum heating, cooling and total loads are 11.4, 31.7 and 43.1 kW h/m^2a, respectively, in envelope 4, whereas in Test 4, these values are 5.5, 20.7 and 26.2 kW h/m^2a, respectively, in envelope

Table 7 Mean *U*-values and corresponding *U*-values of building elements/components Nasrollahi and Nooraei (2013)

	Mean *U*-value (W/m^2 °C)		Building element	*U*-value (W/m^2 °C)		Insulation thickness (mm)
	Tests 1 and 2	Tests 3 and 4		Tests 1 and 2	Tests 3 and 4	
7	1.05	0.74	Wall	0.50	0.50	58
			Roof	0.21	0.21	160
			Ground floor	1.06	1.06	26
			Exposed floor	0.21	0.21	160
			Window glazing	2.86	1.29	–

Table 8 Results of energy efficiency of case study I with ECBC compliant condition

Condition	Condition I	Condition II	Condition III	Parametric case
Total heat input in watts.	524250	212840	241826	149037
Percentage of heat input	100%	40.60%	46.13%	28.43%
Percentage efficiency above/below ECBC		Base	13.62% below	29.97% above

Table 9 Results of energy efficiency of case study II with ECBC compliant condition

Condition	Condition I	Condition II	Condition III	Parametric case
Total heat input in watts.	230850	107252	88857	76329
Percentage of heat input	100%	46.46%	38.49%	33%
Percentage of efficiency above/below ECBC		Base	17% above	28.8% above

Table 10 Results of energy efficiency of case study III with ECBC compliant condition

Condition	Condition I	Condition II	Condition III	Parametric case
Total heat input in watts.	101120	40705	43124	28294
Percentage of heat input	100%	40.25%	42.65%	28%
Percentage efficiency above/below ECBC		Base	5.96% below	30.5% above

7. Since there is considerable reduction in heating, cooling and total load in Test 4 than in Test 2 as mentioned above, results of all three case studies have been compared with results of Test 4 by replacing the *U*-values of proposed condition IV with the optimum mean *U*-values of Test 4 which is 0.74 W/m^2 °C. Against mean *U*-value of 0.74 of envelope 7, corresponding *U*-values of wall, roof and fenestration have been taken as 0.50 for wall, roof 0.21 and for fenestration (window glazing) 1.29 W/m^2 °C, and SHGC as 0.2 as given in Table 7.

Analysis has been made by replacing the *U*-values of condition IV given in Tables 1, 2 and 3 with the optimum

U-values in Table 7 for all the case studies. This condition is described as parametric case in Tables 8, 9 and 10. In this analysis, condition II (ECBC compliant condition) has been considered as the base case to define the optimum level of insulation with respect to *U*-values prescribed by ECBC. The results of energy efficiency of actual building and parametric case with respect to ECBC compliant condition are given in Tables 8, 9 and 10 for case study I, II and III, respectively.

It is observed from Table 8 that energy efficiency in case study I of actual building condition is 13.62% less and of parametric case 29.97% more than ECBC compliant conditions. In Table 9, energy efficiency in case study II of actual building condition is 17% more and of parametric case 28.8% more than ECBC compliant conditions, while in Table 10, energy efficiency in case study III of actual building condition is 5.96% less and of parametric case 30.5% more than ECBC compliant conditions.

From parametric cases of case study I, II and III, it is observed that energy efficiency is 28.8–30.5% more than ECBC compliant conditions indicating that optimum level of insulation can be interpolated to 30% above *U*-values prescribed by ECBC.

Conclusion

The design of the building plays a vital role in energy efficiency. The building envelope of *U*-values prescribed by ECBC enhances the energy efficiency in a building. Though DGU with high-performance glass increases the energy efficiency, DGU with low-e glass provides higher energy efficiency than solar reflective DGU.

Although energy efficiency increases with increase in insulation of the building envelope but after reaching certain limit, there is no substantial increase in energy efficiency and thus further increase in insulation does not remain cost-effective. The paper investigates this optimum level of insulation of building envelope with respect to ECBC prescribed provisions.

In the present investigation, three case studies have been considered, two of composite climate and one of warm and humid climate. Energy efficiency has been determined by comparing the *U*-values of the three case studies, *U*-values found against the optimum total load from the tests conducted by Nasrollahi and Nooraei (2013) with respect to *U*-values prescribed by ECBC for various climate zones. It is found that the optimum level of the insulation is 30% above the *U*-values prescribed by ECBC.

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