Environmental Optimization of Building Insulation Thickness in Warm-Dry Regions

E. Anbarzadeh[1,*], S. M. Ghafoori Yazdi[1]

[1] *Department of Mechanical Engineering, Faculty of Engineering, Kharazmi University, Tehran, Iran.*
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Abstract

In this study, the environmental effect (CO_2) of rock wool as a mineral insulation material and expanded polystyrene as a polymer insulation material for a residential building is studied. Initially, the intended building is simulated in Design Builder for warm-dry climate regions like Yazd and Isfahan cities and then the effect of different thicknesses of these two insulation materials inside the external wall of the building is studied towards optimizing the thickness value environmentally. Despite the CO_2 emissions generated by cooling and heating systems while consuming energy throughout the year, embodied CO_2 values in the manufacturing process until installation are also considered. Eventually, using the Energy Plus simulation engine inside Design Builder and MATLAB software, the environmental optimum insulation thickness regarding emission and embodied values of CO_2 for a lifetime of ten years in warm-dry regions of Iran such as Yazd and Isfahan cities are calculated. These values for expanded polystyrene are found to be 20 cm for Isfahan and 19 cm for Yazd and values for rock wool are 11 cm for Isfahan and 10 cm for Yazd. Thus, a mineral insulation material such as rock wool has a smaller environmental optimum insulation thickness than a polymer insulation material such as expanded polystyrene.

Keywords: Thermal Insulation, Optimum Insulation Thickness, Environmental Analysis.

1. Introduction

Considering the facts like significant increase in population in the last decade, recent changes in the climate due to destruction of the ozone layer, more urban activities taking place as a result of cities becoming more and more industrialized and immigrations to large cities so that nowadays the buildings section produces 25% of the total CO_2 and consumes 25%-40% of the total global energy [1], the necessity of thermal protection in residential buildings is felt more than ever. One of the most common solutions to reducing energy loss which is usually in the envelope of buildings is thermal insulation [2]. Also, CO_2 production will significantly decrease by using thermal insulation [3]. It must be noted that increasing the thickness of insulation will lead to a decrease in CO_2 production and costs associated with energy consumption and a raise in costs and CO_2 production associated with insulation production and installation [4]. Thus, an optimization procedure must be applied to get the most out of a building at both construction and operation phases. The first step towards optimization is an accurate simulation of heating and cooling loads and for this, different buildings thermal activity simulation softwares such as BLAST, SPARK, MATLAB and DOE-2 were developed [5-7]. Underwood et al solved the buildings thermal activity mathematical mode equation for the first time in 1999 using Simulink [8,9] and since then, mathematical models that describe building thermal activity have been more noticed. After that, Mendes et al [10,11] developed energy equilibrium equations in buildings with transient conditions and solved them by using numerical methods [12]. One of the simplest methods that is applied under static conditions to evaluate transmission loads is the degree-day/hour method. Alsayed and Tayeh [13], Sagbansua and Balo [14], and Kurekci [15] all used this method to determine the optimum insulation thickness for their case. On another hand, a limited number of studies evaluated the transmission load by using the more accurate transient heat transfer methods under dynamic conditions. Furthermore, Özel et al [16,17]. indicated that determining the optimum insulation thickness must be done by considering two parameters: environment and economy. Moreover, Ozkan and Onan [18] carried out an additional environmental analysis to prior ones to investigate the effects of the type of fuel and insulation material in four different climate zones. E. Amiri [19] illustrates the importance of considering embodied carbon and embodied energy into account when determining the optimum insulation thickness while carrying out a 3E analysis [20]. In this study, a sample building from mass construction maps is chosen and modelled using Design Builder which is one of the most complete softwares in thermal analysis. The sample building is initially drawn then walls construction, openings, cooling and heating systems, building application, etc… are applied to

*Corresponding author
Email address: ehsananbarzadeh74@gmail.com

finally calculate the corresponding thermal load, The energy simulation engine of this software is Energy Plus which is built by U.S department of energy and is one of the most accurate softwares in energy basis and has a very high calculation accuracy. Insulation materials used in this study are Expanded Polystyrene (EPS) which is one of the most commonly used insulation materials and rock wool. Simulations are carried out for two cities in Iran with warm-dry climate which are Yazd and Isfahan. Then, embodied CO_2 and emission values resulted from simulations are fed into a code in MATLAB to determine the optimum insulation thickness. The thickness with least total CO_2 emissions is taken to be the optimum. Eventually, results for both insulation materials are compared to each other.

2. Case Study

The intended building plan is chosen from mass construction maps to be a typical 4 story, 16 units building. East sided apartments are 96 square meters, west sided apartments are 128 and the overall foundation is 1780 square meters. Fig. 1. shows the plan of one floor of the building.

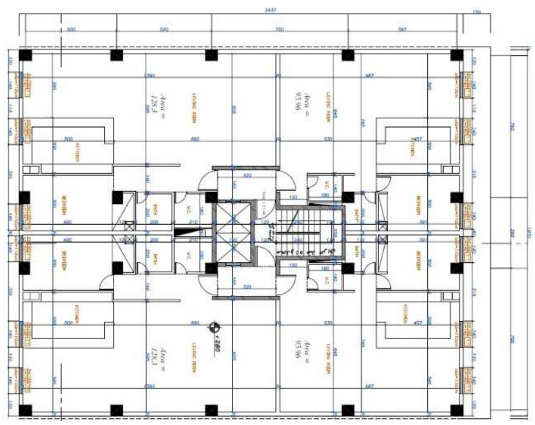

Fig. 1. Floor plan.

The ground floor contains the parking, storerooms and the janitor room and every apartment contains two bedrooms, a bathroom, a washroom and a kitchen. Four people with an adult metabolism are considered in every apartment.
Using Design Builders features, walls construction, openings, cooling and heating systems, building application, schedules of lightings, occupants and different equipment are configured.

energy consumption and CO_2 emissions. etc… are accurately applied and even operating The final model of the building from Design Builder is presented in Fig. 2., in which parts such as the compound and trusses aren't modelled because they don't affect thermal calculations.

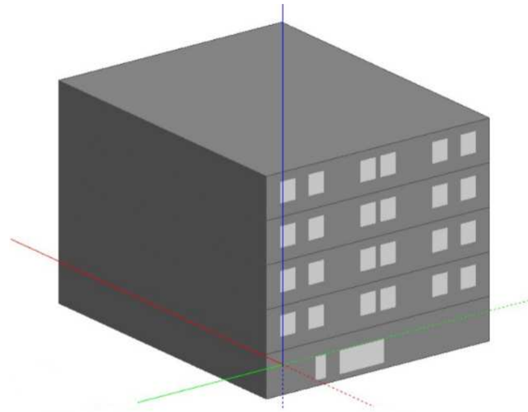

Fig. 2. Case study building modelled in design builder software.

2.1. Climate

Fig. 3. shows the regional map of Iran with considered cities pointed to and Geographic specifications of the cities are presented in Table. 1..

Fig. 3. Climate zones of Iran and selected cities in this study.

Table. 1. Certain Data for Selected Cities.

City	Climate	Elevation (m)	Longitude (deg)	Latitude (deg)	Winter outdoor design temperature (^oC)	Summer outdoor design temperature (^oC)
Isfahan	Moderate	1549	51.67	32.47	-8	43
Yazd	Warm dry	1237	54.28	31.89	-4	47

2.2. The Structure of External Walls

External insulation of buildings reduces the need for space heating and cooling. Additional benefits include increased occupant comfort, reduced requirements for heating and cooling systems capacity. In this study, a hypothetical house is considered with the external wall built as composite structure, which is generally formed with bricks in the middle, plaster layers on both sides, insulation material on the inside of the brick layer and granite on the most outside layer.
This structure is used for heat losses calculations of external walls for all cities considered. The structure of the external wall is shown in Fig. 4..
The structure of external wall consists of 2 cm inner plaster (k=0.698 $W\,m^{-1}\,K^{-1}$), insulation material (expanded polystyrene standard, k = 0.03 $W\,m^{-1}\,K^{-1}$ and Rock wool, k=0.04 $W\,m^{-1}\,K^{-1}$), 10 cm horizontal hollow brick (k=0.485 $W\,m^{-1}\,K^{-1}$), 1.5 cm mortar (k=0.83 $W\,m^{-1}\,K^{-1}$) and 1.5 cm outer granite stone (k=3.49 $W\,m^{-1}\,K^{-1}$). In this study, the thickness of insulation material is considered as a variable to be optimized therefore it changes with every simulation.

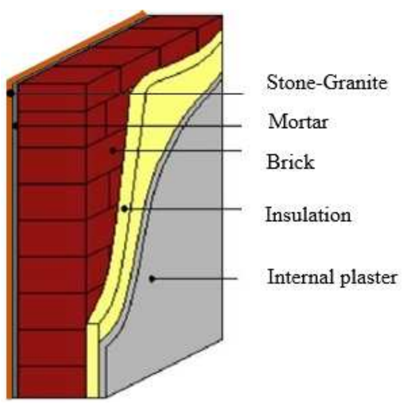

Fig. 4. Structure of the investigated external wall.

3. Methodology

Embodied carbon over a life cycle of a building is generated through a cycle that starts with the extraction of raw materials and ends with buildings life end as follows:
1. Extraction of raw materials,
2. Transportation of raw materials to manufacturer.
3. Manufacturing building materials.
4. Transportation to site.
5. Construction.
6. End of building life.

The amount of the total CO_2 as the sum of the produced CO_2 from the energy consumption in cooling and heating sections in the operation phase and embodied carbon of the insulation was obtained from Energy Plus simulation engine inside Design Builder software which can be also calculated using Eq. (1). [20]:

$$CO_{2_t} = N \times \left(CO_{2_{el}} + CO_{2_g}\right) + \left(CO_{2_0} \times M_{ins}\right) \qquad \textbf{Eq. 1}$$

In which CO_{2_t} refers to total produced CO_2, $CO_{2_{el}}$ indicates the amount of CO_2 produced from annual electricity consumption and CO_{2_g} indicates the amount of CO_2 produced from annual gas consumption which can be both calculated using Eq. (3). and Eq. (4). Also, the mass of the insulation M_{ins} can be calculated using Eq. (2). and CO_{2_o} refers to the embodied carbon per mass unit of the insulation[20].

$$M_{ins} = A_w \times \rho_{ins} \times X_{ins} \qquad \textbf{Eq. 2}$$
$$CO_{2_{el}} = EL \times EF_e \qquad \textbf{Eq. 3}$$
$$CO_{2_g} = G \times EF_g \qquad \textbf{Eq. 4}$$

In above equations the thickness of insulation, density of insulation, and area of the wall building, were shown by X_{ins}, ρ_{ins}, and A_w receptively. Moreover, EF_e and EF_g refer to carbon emission factors for electricity and gas.

4. Results and discussion

In this study, the optimum insulation thickness of a typical house at two different cities in Iran has been environmentally studied. As it can be seen from Fig. 5. and Fig. 6., CO_2 emissions produced from energy consumption inside the building decreases as the insulation material thickness increases.
The decrease in CO_2 emissions by using EPS is more than by using rock wool. It can also be seen from Fig. 7. that with the increase of insulation material thickness, embodied CO_2 values also increase and this increase is more significant for EPS than rock wool which clearly shows the devastating environmental effects (CO_2) of producing expanded polystyrene insulation material.
By summing the embodied CO_2 values with annual CO_2 emissions for a ten year period, Fig. 8. and Fig. 9. are produced and the optimum insulation thickness can be derived from them.
The environmental optimum insulation thickness for EPS insulation is found to be 20 cm for Isfahan city and 19 cm for Yazd.
Also, the environmental optimum insulation thickness for rock wool is found to be 11 cm for Isfahan and 10 cm for Yazd. It must be noted that only the environmental aspect has been taken into account for the determination of the optimum thickness.
Therefore, the optimum insulation thickness is found to be so high because of the absent of other aspects like economy.
Overall, regarding prior studies is Iran, the optimum insulation thickness from an energy-economical

aspect for EPS has an average value between 4 cm and 5 cm and for rock wool, it has an average value between 8 cm and 10 cm.

Using results from this study, a 4 to 5 cm thickness of EPS has a total CO_2 emissions of 455 $kg\ m^{-2}$ for Isfahan city and 425 $kg\ m^{-2}$ for Yazd.

Also, an 8 to 10 cm of rock wool insulation has a total CO_2 emissions of 435 $kg\ m^{-2}$ for Isfahan city and 420 $kg\ m^{-2}$ for Yazd.

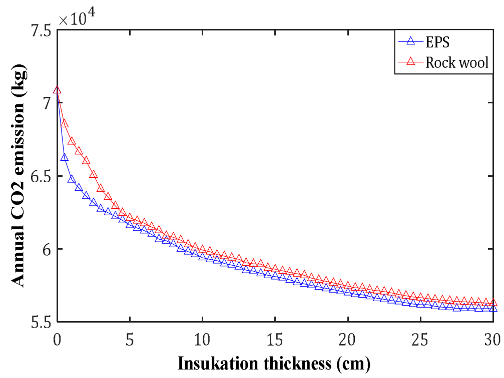

Fig. 5. Effect of insulation thickness on annual CO_2 emissions in Isfahan city.

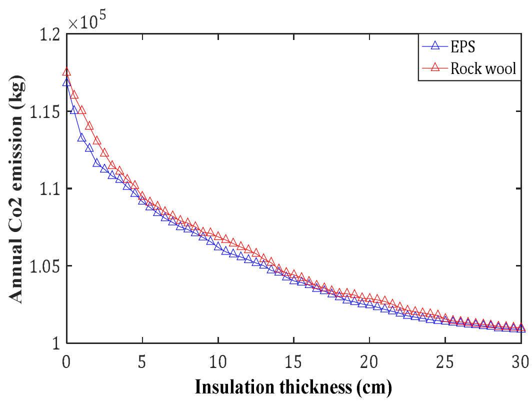

Fig. 6. Effect of insulation thickness on annual CO_2 emissions in Yazd city.

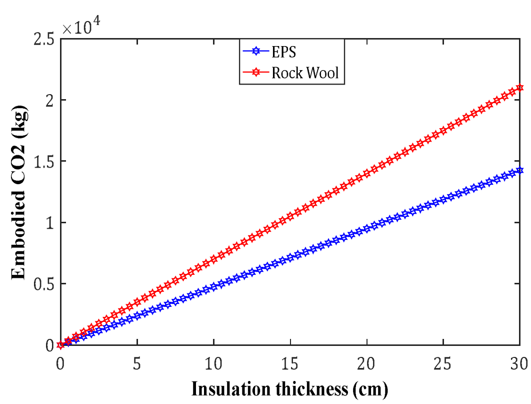

Fig. 7. Variations of embodied CO_2 vs insulation thickness.

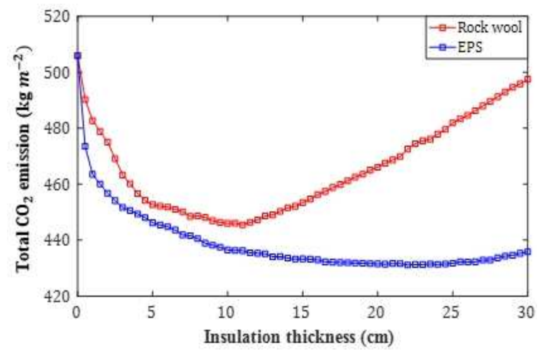

Fig. 8. Total CO_2 emissions for different insulation thicknesses in Isfahan.

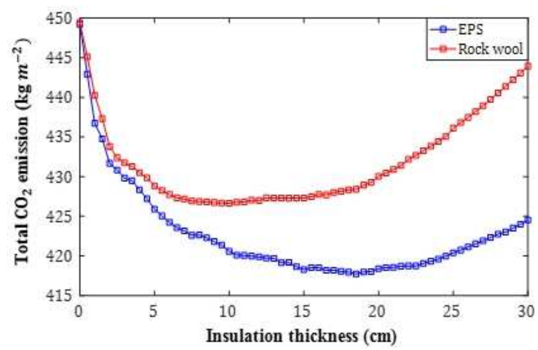

Fig. 9. Total CO_2 emissions for different insulation thicknesses in Yazd.

5. Conclusions

One of the best ways to reduce buildings energy consumption, overall cost and total CO_2 emissions is to limit heat loss/gain through external walls. This study’s overall conclusions are:

1. An environmental optimum insulation thickness for a lifetime of 10 years was calculated for two selected cities with warm-dry climate in Iran which are Isfahan and Yazd.
2. As resulted, any increase in insulation thickness leads to a decrease in CO_2 emissions. But the increase in insulation thickness towards reducing energy consumptions and CO_2 emissions causes an increase in embodied CO_2 values. Hence, to determine an environmental optimum insulation thickness both embodied and emission values of CO_2 must be taken into account.
3. Results also show that expanded polystyrene which is a polymer insulation material has more harmful effects on the environment while also having a bigger optimum insulation thickness.
4. The use of a mineral insulation material such as rock wool is more environment friendly.

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