Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879

Optimum Thermal Insulation Thickness for Building Under Different Climate Regions - A Review

Open Access

Eltahir Khalid Mohammed Abdelgadir[1], Ali Mohammed Hamdan Adam[2], Obai Younis[3,4,*], Ahmed Kadhim Hussein[5]

[1] Department of mechanical Engineering, University of Nyala, Nyala, Sudan
[2] Department of mechanical Engineering, University of Bahri, Khartoum, Sudan
[3] Department of mechanical Engineering, College of Engineering at Wadi Addwaser, Prince Sattam Bin Abdulaziz University, Wadi Addwaser, KSA
[4] Department of mechanical Engineering, Faculty of Engineering, University of Khartoumi, Khartoum, Sudan
[5] College of Engineering, Mechanical Engineering Department, University of Babylon, Babylon City, Iraq

ARTICLE INFO

Article history:
Received 18 March 2019
Received in revised form 26 May 2019
Accepted 26 June 2019
Available online 20 July 2019

ABSTRACT

This review paper aims to provide an updated review of the literature on the optimum thermal insulation thickness for building under different climate regions. However, there is a limited amount of literature that has been published recently to determine the optimum thermal insulation thickness in different climates regions by using a different insulation materials and various techniques in the analysis This study therefore provides an excellent road map on determination of the optimum insulation thickness in buildings and its impact on the environment and the energy saving. Different insulation materials, different optimization and the economic analysis methods which are used in the studies were presented and summarized in a useful table. The present paper also presents the concept of the optimum thermal insulation and the selection of insulation materials in an economical way to give the minimum cost which is necessary to reduce the energy consumption and the environmental pollution in different countries. The degree-time method which is considered the most common method used in studies to calculate the heating and cooling loads is also explained. Moreover, the most commonly method used for the thermal insulation thickness optimization for building which is called the life cycle cost (LCC) analysis is also investigated.

Keywords:
Optimum thermal insulation thickness; Insulation materials; Degree day; Life cycle cost; Literature review

1. Introduction

Energy is the most important factor of economic and social development and it is considered as important criteria to improve the quality of life in all countries. Consumption of energy worldwide is increasing due to increasing population and the huge improvements in the standard of living. The energy sources are limited and the combustion of the fossil fuel polluted to the environment. The

**Corresponding author.*
E-mail address: oubeytaha@hotmail.com (Obai Younis)

consumption of energy is divided to four main sectors, namely building, industrial, transportation and agriculture. In many countries the energy required in buildings for space cooling and heating has the highest share compared to others [1,2] . Also, the consumption of energy in buildings accounts approximately 40 % of the global consumption especially in the developing countries. From the other side, the energy requirement for the space cooling and heating of a building is approximated 60 % of the total energy consumed in them, which accounts for the largest percentage of the energy usage [3-7]. The use of the thermal insulation in buildings plays also a major role to reduce the dependence on heating, ventilation, and air conditioning (HVAC) systems to operate buildings comfortably and therefore, save energy and the associated natural resources. It is considered as one of the most successful means to reduce the heat transfer through the buildings [8]. Insulation system reduces also polluting products such as CO_2, CO, SO_2 and the dust particles.

Furthermore, the insulation also improves the internal thermal comfort conditions by reducing the heat losses or gains from or to buildings in cold and hot seasons. In addition, the insulation material type which is considered also as an important factor. Although, the heat loss and gain decrease with increasing the insulation thickness, the total cost of insulation include the material and installation costs also increase. For that reason, the most researchers determined the optimum insulation thickness respected to the costs [4,6,9-11]. The insulation thickness is a function of various parameters, such as the building function, type, shape, orientation, building materials, insulation material and cost, climatic conditions, fuel type and cost and the type and efficiency of an air-conditioning system. Also, many studies have estimated the optimum thermal insulation materials thickness used in building walls for different climate conditions.

The present paper includes an amount of literature that has been published recently to determine the optimum thermal insulation thickness in different climates region used different insulation materials and different techniques for analysis and not covered in the previous published review papers. The paper discusses the following aspects, the effects of thermal insulation used in building walls on reducing energy consumption, methods of determination of optimum insulation thickness for different wall configurations, and the properties of thermal insulation materials and their applications in building envelopes. The amount of the literature review reported and summarized in this paper provides an easy and quick access for researchers interested in thermal insulation.

The literature reviews focused on the determination of optimize insulation thickness for different components of building throughout the world from different points of view. The main purpose of the present paper is to provide an updated overview of recent developments in the literature to improve the energy performance of residential buildings sector. Aynur and Figen [1] calculated the optimum insulation thickness of the external wall, energy savings and payback periods for four cities from four climate zones of Turkey, for lifetime of ten years. A five different energy types and four different insulation materials were applied on external walls. Ömer and Faruk [4] calculated the optimum thermal insulation thicknesses on external walls of buildings for four degree-day regions in Turkey, namely, Iskenderun, Istanbul, Ankara and Ardahan based on both annual and seasonal energy loads.

Okan [5] determined the optimum insulation thicknesses by using economic analyses for external walls in buildings used different masses in five different cities had a different climate regions in Turkey. Duman *et al.,* [6] estimated the optimum insulation thickness for building envelop in three different demo-sites located in Europe. They provided an economic and energy cost optimization, which had a positive effect on reducing the energy demand and greenhouse gases emissions. Cenker and Ugur [7] determined the optimum insulation thickness for the external walls for buildings in Turkey based on different materials, energy sources and climate regions for four different selected cities in Turkey , namely Mugla, Kocaeli, Ankara and Ardahan.

Nematchoua *et al.,* [8] determined the optimum insulation thickness, energy saving and payback period for buildings located in two climatic regions in Cameroon. Dombayci *et al.,* [9] calculated the optimum insulation thickness of external walls, energy saving and impact of emissions of CO_2 and SO_2 for different climate regions in Turkey. Jihui Yuan *et al.,* [11] calculated the optimum insulation thickness for the external walls of buildings in 32 regions of China to save the energy and reduced CO_2 emissions. In another work , Kurekci [12] was determined the optimum insulation thicknesses required in Turkey's 81 provincial centers. The calculations were made on four different fuels and five different insulation materials. Three different cases were considered, namely buildings heated but not cooled, cooled but not heated, and both heated and cooled. The optimum insulation thicknesses for each case were computed. Kaynakli *et al.,* [13] used the life cycle cost to find the optimum insulation thickness. The results showed that this thickness was increased by increasing the heating and cooling energy requirements over lifetime of the building and energy costs. Nematchoua *et al.,* [14] presented the economical and optimum thermal insulation thickness for buildings in cold and hot tropical climate in Cameroon . The economic model used over a lifetime of 22 years of the building to calculate the optimum insulation thickness, energy saving and payback period. Hamdan and Malek [15] used MATLAB software to calculate the optimum insulation thicknesses which were used to minimize the cost of the consumed heating load in residential building located in Amman, Jordan. Siddique *et al.,* [16] determined the optimum insulation thickness on exterior walls and roofs based on the peak cooling loads for an existing residential building in Lahore, Pakistan. Nurullah and Abdulvahap [17] investigated the efficient parameters on the optimum insulation thickness in terms of the order of importance using theoretical-Taguchi coupled method. Four different cities in Turkey were selected for analysis, namely Izmir, Istanbul, Ankara, and Erzurum.

Özel *et al.,* [18] determined economically the optimum insulation thicknesses and environmental impact for rock and glass wools in Bilecik, Turkey. Firstly, the entransy loss, the fuel consumption and CO_2 emissions were calculated. Secondly, according to the entransy, the environmental impact of the system and the total cost were computed also. Marif *et al.,* [19] determined the thermal performance of interior and exterior wall insulations for buildings in the South of Algeria. They concluded that there was no difference between the interior and exterior wall insulations except that the interior surface temperature was dropped much faster in the case of the interior insulation. Alghoul *et al.,* [20] studied the effected of electricity price on residential heating and cooling energy consumption and on the insulation thickness in Tripoli, Libya. Singh *et al.,* [21] estimated the optimum insulation thickness, payback periods and life cycle savings utilizing life cycle cost analysis in composite climatic zone of India. Cyrille Vincelas and Ghislain [22] presented a comparative study for the calculation of the most economical combination between external wall and optimum insulation thickness for energy saving in Cameroonian's buildings. The degree-day's concept was used to determine the yearly cooling transmission loads of the building. Moreover, P1-P2 method was used in economic analysis to determine the optimum insulation thickness, energy savings, and payback period for buildings. Altan Dombayci *et al.,* [23] calculated the optimum insulation thickness of exterior walls for the houses in the selected provinces of Izmir, Ankara, Trabzon and Kars in Turkey by using thermo-economic method together with the LCA method.

2. The Significance of The Thermal Insulation

Thermal insulations are materials or combinations of materials that are used primarily to provide a resistance to the heat flow. A thermal insulator is a poor conductor of the heat and has a low thermal conductivity. Insulation is used in buildings and in manufacturing processes to prevent the heat loss or gain. Although, its primary purpose is an economic one, it also provides more accurate control of the process temperatures and protection of personal. It prevents the condensation on cold surfaces and the resulting corrosion. Such materials are porous, containing large number of dormant air cells [24].

The thermal insulation for the building walls is considered one of the more effective means to reduce the energy consumption for cooling or heating in buildings, in time which the demand increasing for the electricity as a result of increasing population, expansion and development plans, and maintaining a good comfort conditions. Besides, the increasing cost of energy and adverse impact on the environment by energy production plants, all contribute to find means to substantially reduce the energy consumption. The application of the thermal insulation on the structure of external walls are three type; internally, externally and sandwiched. The structure of the external wall is illustrated in Figure 1. It consists of inner plaster, horizontal hollow brick, insulation material and an external plaster. The structure of the sandwich-type wall shown in Figure 2, which consists of the internal plaster, horizontal hollow brick, insulation material, horizontal hollow brick, and the external plaster.

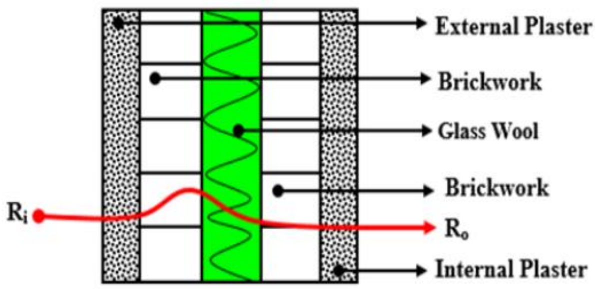

Fig. 1. Structures of the sandwiched wall [7]

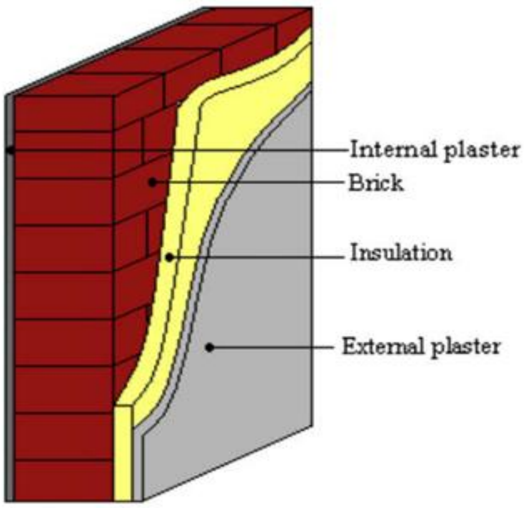

Fig. 2. Structures of the external wall [1]

3. Types of Insulation Materials

The selection of proper type of insulation materials depends on various factors such as the thermal conductivity, density, and the cost of insulation materials. There are several types of insulation materials had been selected in the previous studies for determination of the optimum thermal insulation thickness. Ömer and Faruk [4] applied the polystyrene as an insulating material in calculations with density of 30 kg/m^3 and thermal conductivity of 0.030 W/m.K. Okan [5] considered the glass wool, expanded polystyrene (EPS), extruded polystyrene (XPS) as an insulation materials. Lowest optimum insulation thickness was determined by using the extruded polystyrene (XPS) as an insulation material. While, the highest one was determined by using the glass wool. Nematchoua *et al.,* [8] selected the extruded polystyrene as an insulation material and applied it on two typical wall structures, namely the concrete block and compressed stabilized earth block wall. Kurekci [12] considered five different insulation materials which were extruded polystyrene, expanded polystyrene, glass wool, rock wool and polyurethane. Kaynakli *et al.,* [13] used polystyrene expanded or extruded and rock wool as insulation materials in their study. Nematchoua *et al.,* [14] employed extruded polystyrene in their analysis. Cenker and Ugur [7] examined in their study, the insulation material to detect its optimum thickness, as well as its energy savings over a period of 15 years. The sandwich type insulated wall was examined considering six different insulation materials, namely extruded polystyrene (XPS), expanded polystyrene (EPS), glass wool (GW), rock wool (RW), polyisocyanurate (PIR), and polyurethane (PUR) with their thermal conductivities 0.031, 0.039, 0.040, 0.040, 0.024 and 0.023 W/m.K respectively. Hamdan and Malek [15] determined the optimum insulation thicknesses based on life cycle cost analysis for three wall configurations using extruded polystyrene, expanded polystyrene and polyurethane boards as insulation materials. Nurullah and Abdulvahap [17] used the insulation materials in calculations , namely an extruded polystyrene (XPS) with thermal conductivity, k = 0.031 W/m.K , expanded polystyrene (EPS) with thermal conductivity, k= 0.039 W/m.K, glass wool with thermal conductivity, k=0.040 W/m.K and polyurethane with thermal conductivity, k= 0.024 W/m.K. Dombayci *et al.,* [9] considered the expanded polystyrene and polyurethane as an insulation materials for their analysis. Özel *et al.,* [18] investigated the optimum insulation thickness according to the entransy loss. Their investigation was carried out by using rock and glass wools as insulation materials. CyrilleVincelas and Ghislain [22] used in their calculation six insulation materials namely , expanded polystyrene, extruded polystyrene, foamed PVC, foamed polyurethane, perlite and rock and glass wools. Liu *et al.,* [25] showed that the lifecycle total cost of the exterior wall used (EPS) as an insulation material is lower than that used (XPS) as insulation material. They indicated that (EPS) is more economical than (XPS). Also, the optimum thickness of (XPS) was between 0.053 and 0.069 m , while the optimum thickness of (EPS) is between 0.081 and 0.105 m. Lianying *et al.,* [26] applied in their study an expanded polystyrene as insulation materials. Gholizadeh *et al.,* [27] were selected the rock wool, polystyrene and autoclaved aerated concrete (AAC) blocks as an insulation material. Nyers *et al.,* [28] considered the polystyrene as a thermal insulation material. The techno-economical optimum thickness of thermal insulation layer (polystyrene) is 9 cm. Fertelli [29] investigated the optimum insulation thickness, annual energy saving, and payback periods for four different types of external walls, with (XPS) and rock wool as insulation materials. The highest value of the optimum insulation thickness was reached by using wall 1, (XPS) as insulation material, and (LPG) as energy source, whereas the lowest optimum insulation thickness is obtained by using wall 4, rock wool as insulation material and geothermal energy as an energy source. Kayfeci *et al.,* [30] were selected glass wool, Styrofoam and rock wool as insulation materials. BektasEkici *et al.,* [31] utilized an extruded polystyrene, expanded polystyrene, fiber glass, and foamed polyurethane as insulation materials. Subhash Mishra *et al.,* [32] used two different insulation materials in their study namely , glass wool and expanded polystyrene.

Subhash Mishra *et al.,* [33] selected an extruded polystyrene (XPS) and expanded polystyrene (EPS) as insulation material , while Daouas [34] used an expanded polystyrene with the thermal conductivity, k = 0.037 W/m K as insulation materials. Panyu Zhu [35] were utilized an expanded polystyrene (EPS) and extruded polystyrene (XPS) for the same purpose in their study. Moreover, Özden Ağra1 *et al.,* [36] selected an expanded polystyrene as the insulation material in buildings, while Ramin *et al.,* [37] used an expanded polystyrene (EPS) for the same purpose. Saadatian *et al.,* [38] applied three different types of insulation material, namely polyurethane (PUR), extruded polystyrene (XPS) and expanded polystyrene (EPS). Müslüm and Hasan [39] calculated the optimum air layer thickness of double-glazed window for different climate zones in Turkey.

From the literature review mentioned above, the most commonly used insulation materials that gave appropriate results were the expanded polystyrene, the extruded polystyrene and the rock wool respectively. The cost of insulation materials varies greatly and depend on material types. Also the optimum insulation thickness depends greatly on the wall structure, degree-days, and the insulation material.

4. Method of Calculation

One of the most common method used in studies to calculate the heating and cooling loads which is the one of an input parameters used in the determination of the optimum insulation thickness is the degree-time method. This is because the annual heating /cooling energy cost is derived from the annual heating or cooling loads. From the literature review , the degree-time method is used to determine the heating or cooling loads by many studies [1, 2, 4-18, 20, 22, 29-36, 39-46] . It assumes that the energy needs for a building are proportional to the difference between the daily mean outdoor temperature and the base temperature. The base temperature is the outdoor temperature above or below which cooling or heating is needed.

The heat loss from the unit surface of the external wall is given by

$$q = U \times (T_b - T_O) \tag{1}$$

Where U is the overall heat transfer coefficient, T_b is base temperature and To is the mean daily temperature.

The annual heat losses and gains occurring in the unit surface are calculated by using (U) and the degree-day value (DD) as given by the following equations

$$q_{A,H} = 86400 \times HDD \times U \tag{2}$$

$$q_{A,C} = 86400 \times CDD \times U \tag{3}$$

Where *HDD* is the heating degree days and *CDD* is the cooling degree days.

$$HDD = \sum_1^{365} |T_b - T_O| \tag{4}$$

$$CDD = \sum_1^{365} |T_O - T_b| \tag{5}$$

The annual energy requirement can be calculated by dividing the annual heat loss to the efficiency of the heating system (η).

$$E_{A,H} = \frac{86400 \times HDD \times U}{\eta} \tag{6}$$

Similarly, the annual cooling load can be determined in an analogous expression as

$$E_{A,C} = \frac{86400 \times CDD \times U}{COP} \tag{7}$$

The overall heat transfer coefficient (U) for a typical wall with insulation is given by

$$U = \frac{1}{R_i + R_W + R_{ins} + R_O} \quad (8)$$

where R_i and Ro are respectively representing the inside and outside air film thermal resistances, while R_w is the total thermal resistance of the wall without the insulation, and R_{ins} is the thermal resistance of the insulation layer.

The thermal resistance of the insulation layer R_{ins} is given by

$$R_{ins} = \frac{x}{k} \quad (9)$$

where x is the thickness of the insulation layer; k is the thermal conductivity of the insulation material. If R_{wt} is the sum of R_i and R_w , while R_o is the total wall thermal resistance excluding the insulation layer resistance, then Eq. (8) can be re-written as follows.

$$U = \frac{1}{R_{wt} + R_{ins}} \quad (10)$$

The annual energy need for heating ($E_{A,H}$) is calculated as follows.

$$E_{A,H} = \frac{86400 \times HDD}{\left(R_{wt} + \frac{x}{k}\right) \times \eta} \quad (11)$$

While, the annual energy need for cooling ($E_{A,C}$) is calculated as follows.

$$E_{A,C} = \frac{86400 \times CDD}{\left(R_{wt} + \frac{x}{k}\right) \times COP} \quad (12)$$

where COP is the cooling system coefficient of performance.

In the following paragraphs, another previous studies followed different techniques are reviewed. Bolatturk [41] used the degree-hours method with considering the solar radiation in the calculation. Ömer and Faruk [4] investigated the effect of cases considering and not considering the incident solar radiation on the seasonal space heating/cooling loads and used the degree days method. Nematchoua *et al.,* [8, 14] used the numerical solution of the transient heat transfer and compared the results obtained with the degree-day method. Siddique *et al.,* [16] used Autodesk, Revit 2013 for the analysis of the building and determination of the peak cooling loads. Marif *et al.,* [19] developed a computer program based on an implicit finite difference method in order to estimate the thermal performance of the wall in the two cases which were considered in their study. Liu *et al.,* [47] used a numerical solution to investigate the thermal performance of exterior walls of residential buildings with moisture transfer in hot summer and cold winter zones of China. Lianying *et al.,* [26] investigated numerically the effects of building external wall's insulation thickness on the heating and cooling loads. Nyers *et al.,* [28] presented a numerical simulation and a mathematical model of the economic optimum of thermal insulating layer for external wall of brick. Kayfeci *et al.,* [30] used two different methods to determine the annual energy consumption. One of the methods was the degree-hours method, while the second was the method which using the annual equivalent full load cooling hours operation of system.

Ozel [2, 48-49] investigated numerically by using an implicit finite difference method under steady periodic conditions for different wall orientations during the summer period in Antalya, Turkey. Daouas [34] utilized a model of the heat transfer based on the analytical (CFFT) technique to calculate an exact solution of the transient heat transfer through a multi-layer external wall submitted to a steady periodic outdoor temperature and solar radiation specific to the climate of Tunis. The results were compared with the degree-days method. Rahul and Gupta [50] used a computational fluid dynamics (CFD) commercial code (FLUENT) to study the optimum insulation thickness for reefer truck. Panyu Zhu *et al.,* [35] used a formula to calculate the optimum thickness of the thermal insulation layer related to the external wall. Sami and Zedan [51] calculated numerically the yearly cooling and heating transmission loads by using an implicit finite-volume method. Abdul Talib Din *et al.,* [52] produced thermal insulation materials from recycled solid waste and their applications in residential house construction. Recycled materials that were used as specimens are aluminum, plastic, bagasse, textile, oil palm leaves, twigs, paper, corn cob, rubber, coconut husk, coconut shell, granite, wood, iron, glass, kenaf, and concrete. Suhaila Sahat *et al.,* [53] used experimental method and corncob as an alternative insulation material to determine its effectiveness as a thermal insulation material. Ramin *et al.,* [37] applied the dynamic transient model (exact model) rather than the annual heating and cooling degree-days method (crude and approximate one) to calculate the annual heating and cooling demands in the optimization process. The numerical solution of one-dimensional transient heat transfer problem for multi-layer walls was solved to obtain the temperature distribution within the wall in Tehran, Iran. It can be concluded from the above reviewed papers that, the degree-time method is the most common method used in studies to calculate the heating and cooling loads. Few researchers used the numerical investigation of the transient heat transfer and compared the results obtained with the degree-day method.

5. Optimum Thermal Insulation Thickness

It should be realized that the insulation does not eliminate the heat transfer, just it merely reduces it. The thicker the insulation, the lower the heat transfer rate but also the higher cost of the insulation. Therefore, the optimum thickness of insulation is necessary which corresponds to a minimum combined cost of insulation and the heat lost. The determination of the optimum thickness of insulation is shown in Figure 3. It can be seen that the cost of insulation increases linearly with its thickness, while the cost of heat loss decreases exponentially. The total cost, which is the sum of the insulation cost and the lost heat cost, decreases first, reaches a minimum, and then increases. The thickness corresponding to the minimum total cost is the optimum thickness of insulation, and this is the recommended thickness of insulation to be installed [24].

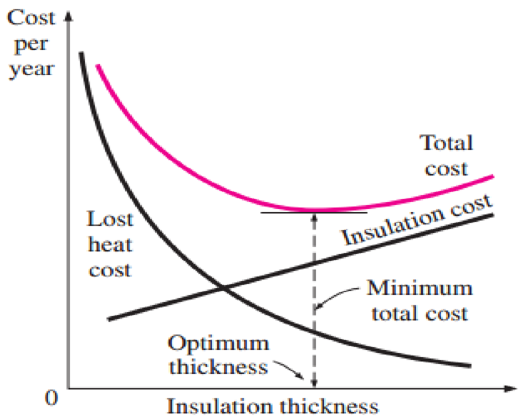

Fig. 3. Computation of the optimum thickness of insulation on the basis of minimum total cost [24]

The discussion above on the optimum thickness is valid when the type and the manufacturer of insulation are already selected, and the only thing to be determined is the most economical thickness. However, often there are several suitable insulations for a job and the selection process can be rather confusing since each insulation can have a different thermal conductivity, different installation cost and a different service life.

6. Annual Energy Cost and Determination of Optimum Insulation Thickness

The most important factor in applying the thermal insulation system is to analyze the thermal insulation with respect to its cost. So from the literature, several economical methods were used to optimize the thermal insulation thickness of external walls. The most commonly used method is so-called the Life Cycle Cost (LCC) analysis which was used in many previous studies [3-7, 11-13, 15, 17, 18, 20, 21, 33, 38, 54]. The annual energy cost for unit surface ($C_{A,H}$) and ($C_{A,C}$) are calculated by using the following equations.

$$C_{A,H} = \frac{86400 \times HDD \times C_f}{\left(R_{wt} + \frac{x}{k}\right) \times H_u \times \eta} \quad (13)$$

$$C_{A,C} = \frac{86400 \times CDD \times C_e}{\left(R_{wt} + \frac{x}{k}\right) \times COP} \quad (14)$$

where C_f in \$/kg is the unit fuel price, $H_u$is the heating value of the fuel, η is the efficiency of the heating system and C_e is the cost of electricity. LCC should be employed when determining the optimum insulating thickness. The total heating cost is evaluated together with the present-worth factor (PWF) for the lifetime of N years. The PWF depends on the inflation rate (g), and the interest rate (i).

If i> g, then

$$r = \frac{i-g}{1+g} \quad (15)$$

While, if i< g , then

$$r = \frac{g-i}{1+i} \quad (16)$$

$$PWF = \frac{(1+r)^N - 1}{r \times (1+r)^N} \quad (17)$$

where N is the lifetime and it is assumed to be 10 years. If i = g, then

$$PWF = \frac{N}{1+i} \quad (18)$$

The cost of insulation (C_{ins}) in \$/m^2 is given by

$$C_{ins} = C_i \times x \quad (19)$$

Where (C_i) in \$/m^3 is the cost of insulation material and (x) is the insulation layer thickness.
The total heating cost of the insulated building is given by

$$C_{t,H} = C_{A,H} \times PWF + C_i \times x \quad (20)$$

While, the total cooling cost of the insulated building is given by

$$C_{t,c} = C_{A,C} \times PWF + C_i \times x \quad (21)$$

Therefore, the total heating and cooling costs of the insulated building is calculated as follows.

$$C_{t,H,c} = C_{A,H} \times PWF + C_{A,C} \times PWF + C_i \times x \quad (22)$$

The optimum insulation thickness minimizing the total heating cost is calculated by using the following equation.

$$x_{opt,H} = 293.94 \times \left(\frac{HDD \times C_f \times PWF \times k}{H_u \times C_i \times \eta}\right)^{1/2} - k \times R_{wt} \quad (23)$$

While, the optimum insulation thickness minimizing the total cooling cost is calculated by using the following equation.

$$x_{opt,C} = 293.94 \times \left(\frac{CDD \times C_e \times PWF \times k}{C_i \times COP}\right)^{1/2} - k \times R_{wt} \quad (24)$$

Therefore, the optimum insulation thickness minimizing the total heating and cooling costs is calculated by using the following equation.

$$x_{opt,H,C} = 293.9 \times \left(\frac{HDD \times C_f \times PWF \times k}{H_u \times C_i \times \eta} + \frac{CDD \times C_e \times PWF \times k}{C_i \times COP}\right)^{1/2} - k \times R_{wt} \quad (25)$$

After calculating the optimum insulation thickness, most studies compute the payback period of the insulation cost.

The payback period can be defined as the amount of time (typically measured in years) to recover the initial investment in an opportunity. This value represents the discounted payback period of the specific thickness compared to the reference thickness. The reference thickness is set to be zero in order to compare the payback period to the un-insulated condition [3].

From the above mentioned literature review, it can be concluded that the optimum insulation thickness was highly affected by the wall structure, degree-days, and the insulation material. In addition, the most common insulation materials have been selected in the previous studies are the expanded polystyrene, the extruded polystyrene and the rock wool. The costs of insulation materials were varied and depended on material types. Table 1 illustrates a summary of various studies in different locations with different methods of calculation and insulation materials used in the analysis.

Table 1
Summary of different studies in various locations with different methods of calculation and insulation materials used in the analysis

Reference	Location/Year	Insulation material/ Thermal conductivity (W/m.K)	Forms of insulation/ Thermal conductivity (W/m.K)	Method of Calculation
Ömer and Faruk [4]	Turkey (Iskenderun, Istanbul ,Ankara and Ardahan) / 2016	Polystyrene with density 30 kg/m^3 and thermal conductivity 0.030 W/m.K	External walls(external plaster) k=0.87 W/m.K, hollow brick, k= 0.45 W/m.K, internal plaster, k=0.87 W/m.K	Heating/cooling degree-day and LCC method
Okan [5]	Turkey(Izmir, Balikesir, Konya and Sivas) / 2017	Glass wool k=0.040 W/m/K, expanded polystyrene ,k= 0.039 W/m.K, extruded polystyrene ,k= 0.031 W/m.K	Exterior walls, internal plaster, k=1.000W/m.K, vertical perforatedbrick k= 0.32 W/m.Kve 0.45W/m.K, outer plaster k=1.600 W/m.K	Heating/cooling degree-day and LCC method
Cenker and Uğur [7]	Turkey (Mugla, Kocaeli, Ankara and Ardahan) / 2017	Extruded polystyrene, expanded polystyrene, glass wool, rock wool, polyisocyanurate, and polyurethane	External wall ,internal plaster, k= 0.87W/m.K, hollow brick, k= 0.84W/m.K, external plaster, k= 0.87W/m.K and $R_{w,t}$= 0.774 m^{2}K/W	Heating/cooling degree-day and LCC method
Nematchoua *et al.,* [8]	Cameroon (Yaounda and Garoua) / 2017	Extruded polystyrene, k=0.04 W/m.K	Wall, cement plaster, k=0.87 W/m.K ,hollow concrete block, k=0.67 W/m.K, CSEB wall, k=0.887 W/m.K	Explicit finite-difference method
Dombayci *et al.,* [9]	Turkey (Ardahan, Aydın, Eskişehir and Samsun) / 2016	Expanded polystyrene, k=0.039 W/m.K and polyurethane, 0.024 W/m.K	Sandwich wall (2 cm inner plaster, two 8.5 cm horizontal hollow bricks and 3 cm exterior plaster)	HDD/CDD and LCC method
Jihui Yuan *et al.,* [11]	China / 2017	Expanded polyurethane	Two kinds of exterior wall structures	HDD/CDD and LCC method
Kurekci [12]	Turkey (Izmir, ˙Istanbul, Ankara, Sivas and Erzurum) / 2016	Extruded polystyrene k=0.031, W/m.KExpanded polystyrene k=0.039 W/m.K, glass wool k=0.040 W/m.K, rock wool (0.040 W/m.K) and polyurethane (0.024 W/m.K)	External wall (internal plaster (lime-based) k=0.87 W/m.K, bricks k=0.45 W/m.K, external plaster (cement-based) k=1.4 W/m.K)	Heating/cooling degree-day and LCC method
Kaynakli *et al.,* [13]	Turkey / 2017	Polystyrene expanded or extruded and rock wool	External wall	Heating/cooling degree-day and LCC method
Hamdan and Malek [15]	Jordan (Amman) / 2017	Extruded polystyrene (0.029 W/m.K), expanded polystyrene (0.033 W/m.K) and polyurethane boards (0.023 W/m.K)	External wall (Stone k=1.70 W/m.K) concrete wall k=1.75 W/m.K, concrete hollow block k= 0.90 W/m.K, plastering k=1.20 W/m.K)	Heating/cooling degree-day and LCC method with MATLAB
Siddique *et al.,* [16]	Pakistan(Lahore) / 2016	Extruded polystyrene	External wall (U-Value= 1.880 W/m^2.K) and roof(U-Value= 1.290 W/m^2.K),	Autodesk® Revit 2013 is used
Nurullah and Abdulvahap [17]	Turkey(Izmir, Istanbul, Ankara,	Extruded polystyrene , expanded polystyrene,	External walls(brick k=0.465 W/m.K, concrete, k=1.74 W/m.K, interior plaster,	Theoretical-Taguchi coupled method with

	and Erzurum) / 2017	,glass wool, and polyurethane	k=0.698 W/m.K, exterior plaster, k=0.872 W/m.K)	HDD/CDD and LCC method
Alghoul *et al.,* [20]	Libya (Tripoli) / 2016	Polystyrene, k= 0.033 W/m.K	External wall, cement plaster, k=0.72 W/m.K, Hollow concrete block, k=1.038 W/m.K,	Heating/cooling degree-day and LCC method
CyrilleVincelas and Ghislain [22]	Cameroon / 2017	Expanded polystyrene, extruded polystyrene, Foamed PVC, Foamed polyurethane, Perlite, Rock wool, Glass wool	Sundry earth block, Hollow concrete block, Compressed earth block, Heavyweight concrete block, Stone, Cement plaster, Plaster board	Heating/cooling degree-day and P1-P2 method was used in economic analysis
AltanDombayci et. al. [23]	Turkey (Izmir, Ankara, Trabzon and Kars) / 2017	Expanded polystyrene, K= 0.039 W/m.K and polyurethane, K= 0.024 W/m.K	External wall (sandwich wall) ,2 cm inner plaster, two 8.5 cm horizontal hollow bricks and 3 cm exterior plaster.	Thermoeconomic method with the LCA method
Liu *et al.,* [25]	China (Harbin, Xi'an, Shanghai, Kunming and Guangzhou) /2015	Expanded polystyrene	External wall	Numerical simulation
Ramin *et al.,* [37]	Iran (Tehran) / 2016	Expanded polystyrene	Walls and roofs, cement plaster, concrete block, gypsum plaster	Dynamic transient model

7. Conclusion

There is an amount of literature that has been published recently to determine the optimum thermal insulation thickness in different climates by using various insulation materials and techniques in the analysis. The present review paper aims to provide an up to date review of the literature related to this subject. These previous studies have been developing and using different techniques to find an accurate solution to optimize the thermal thickness. The present study therefore, provides an excellent literature review on determination of the optimum insulation thickness in buildings and its impact on the environment and energy saving. Different insulation materials, different optimization methods and the economic analysis methods which were used in the reviewed studies were presented. Also, the concept of the optimum thermal insulation and selection of insulation materials in an economical way to give the minimum cost to reduce the energy consumption and the environmental pollution in different countries were presented and discussed.

It can be concluded according to the above literature review, that the optimum insulation thickness was greatly affected by the wall structure, degree-days, and the insulation material. In addition, the most commonly used insulation materials which were used in the previous studies are expanded polystyrene, extruded polystyrene and rock wool. The costs of insulation materials varied and depended on the material types.

The degree-time method is the most common method used in the previous studies to calculate the heating and cooling loads. Few researchers used the numerical investigation of the transient heat transfer and compared the results obtained with the degree-day method. Also, it was found that the most commonly used method to optimize the thermal insulation thickness of external walls is the Life Cycle Cost (LCC) analysis.

References

[1] Ucar, Aynur, and Figen Balo. "Determination of the energy savings and the optimum insulation thickness in the four different insulated exterior walls." *Renewable Energy* 35, no. 1 (2010): 88-94.

[2] Ozel, Meral. "Determination of optimum insulation thickness based on cooling transmission load for building walls in a hot climate." *Energy Conversion and Management* 66 (2013): 106-114.

[3] Kaynakli, Omer. "A review of the economical and optimum thermal insulation thickness for building applications." *Renewable and Sustainable Energy Reviews* 16, no. 1 (2012): 415-425.

[4] KAYNAKLI, Ömer, and Faruk KAYNAKLI. "Determination of Optimum Thermal Insulation Thicknesses for External Walls Considering the Heating, Cooling and Annual Energy Requirement." *Uludağ University Journal of The Faculty of Engineering* 21, no. 1 (2016): 227-242.

[5] Kon, Okan. "Determination of optimum insulation thicknesses using economical analyse for exterior walls of buildings with different masses." *An International Journal of Optimization and Control: Theories & Applications (IJOCTA)* 7, no. 2 (2017): 149-157.

[6] DUMAN, Öykü, Aliihsan KOCA, Rusen Can ACET, Mevlüt Gürsel ÇETIN, and Zafer GEMICI. "A study on optimum insulation thickness in walls and energy savings based on degree day approach for 3 different demo-sites in Europe." In *Proceedings of International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale,* no. CONF, pp. 155-160. LESO-PB, EPFL, 2015.

[7] Aktemur, Cenker, and Uğur Atikol. "Optimum Insulation Thickness for the Exterior Walls of Buildings in Turkey Based on Different Materials, Energy Sources and Climate Regions." *International Journal of Engineering Technologies-IJET* 3, no. 2 (2017).

[8] Nematchoua, Modeste Kameni, Paola Ricciardi, Sigrid Reiter, and Andrianaharison Yvon. "A comparative study on optimum insulation thickness of walls and energy savings in equatorial and tropical climate." *International Journal of Sustainable Built Environment* 6, no. 1 (2017): 170-182.

[9] Dombayci, Ö. Altan, Harun Kemal Ozturk, Öner Atalay, Şengül Güven Acar, and Eylem Yilmaz Ulu. "The impact of optimum insulation thickness of external walls to energy saving and emissions of CO_2 and SO_2 for Turkey different climate regions." *Energy Power Engineering* 8 (2016): 327-348.

[10] Yildiz, Abdullah, Gokhan Gurlek, Mehmet Erkek, and Necdet Ozbalta. "Economical and environmental analyses of thermal insulation thickness in buildings." *Journal of Thermal Science and Technology* 28, no. 2 (2008): 25-34.

[11] Yuan, Jihui, Craig Farnham, and Kazuo Emura. "Optimum insulation thickness for building exterior walls in 32 regions of China to save energy and reduce CO2 emissions." *Sustainability* 9, no. 10 (2017): 1711.

[12] Kurekci, Nuri Alpay. "Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers." *Energy and Buildings* 118 (2016): 197-213.

[13] Kaynaklı, Ö., A. S. Canbolat, and A. H. Bademlioğlu. "A study on the parameters affecting insulation thickness on external wall of buildings." *International Journal of Mechanical and Production Engineering* 5, no. 7 (2017): 81-84.

[14] Nematchoua, Modeste Kameni, Chrysostôme RR Raminosoa, Ramaroson Mamiharijaona, Tchinda René, José A. Orosa, Watis Elvis, and Pierre Meukam. "Study of the economical and optimum thermal insulation thickness for buildings in a wet and hot tropical climate: Case of Cameroon." *Renewable and Sustainable Energy Reviews* 50 (2015): 1192-1202.

[15] M. Hamdan and Malek M. K., "Optimization of insulation thickness for building's external wall in Jordan." *In Conference Paper February* 2017.

[16] Siddique, Sibgha, and Sabahat Arif. "Optimum Insulation Thickness for Walls and Roofs for Reducing Peak Cooling Loads in Residential Buildings in Lahore." *Mehran University Research Journal of Engineering and Technology* 35, no. 4 (2016): 523-532.

[17] Arslanoglu, Nurullah, and Abdulvahap Yigit. "Investigation of efficient parameters on optimum insulation thickness based on theoretical-Taguchi combined method." *Environmental Progress & Sustainable Energy* 36, no. 6 (2017): 1824-1831.

[18] Özel, Gülcan, Emin Açıkkalp, Burak Görgün, Hasan Yamık, and Necmettin Caner. "Optimum insulation thickness determination using the environmental and life cycle cost analyses based entransy approach." *Sustainable Energy Technologies and Assessments* 11 (2015): 87-91.

[19] Y. Marif, M.B.H., M. Zerrouki and M. Belhadj. "Thermal performance of internal and external wall insulation in existing buildings in the South of Algeria." *ISESCO Journal of Science and Technology* 9, no. 16 (2013): 53-59.

[20] Alghoul, Samah K., Ammar O. Gwesha, and Abdurrauf M. Naas. "The effect of electricity price on saving energy transmitted from external building walls." *Energy Research Journal* 7, no.1 (2016): 1-9.

[21] Singh, Hemant Kumar, Ravi Prakash, and K. K. Shukla. "Economic and environmental benefits of roof insulation in composite climate of India." *History* 1, no. 4 (2015): 397-403.

[22] Vincelas, Fohagui Fodoup Cyrille, Tchuen Ghislain. "The determination of the most economical combination between external wall and the optimum insulation material in Cameroonian's buildings." *Journal of Building Engineering* 9, (2017): 155–163.

[23] Dombayci, Ö. Altan, Öner Atalay, Şengül Güven Acar, Eylem Yilmaz Ulu, and Harun Kemal Ozturk. "Thermoeconomic method for determination of optimum insulation thickness of external walls for the houses: Case study for Turkey." *Sustainable Energy Technologies and Assessments* 22 (2017): 1-8.

[24] Cengel, Yunus A., *Heat Transfer: A Practical Approach* 2nd ed. McGrawHill Boston, MA, 2003.

[25] Liu, Xiangwei, Youming Chen, Hua Ge, Paul Fazio, and Guojie Chen. "Determination of optimum insulation thickness of exterior wall with moisture transfer in hot summer and cold winter zone of China." *Procedia Engineering* 121 (2015): 1008-1015.

[26] Lianying, Zhang, Wang Yuan, Zhang Jiyuan, Liu Xing, and Zhang Linhua. "Numerical Study of Effects of Wall's Insulation Thickness on Energy Performance for Different Climatic Regions of China." *Energy Procedia* 75 (2015): 1290-1298.

[27] Farzane Gholizadeh, H. R. Saba, and E. Shakeri. "Impact of insulation on reduction of energy consumption in buildings based on climate in Iran." *American-Eurasian Journal of Agricultural & Environmental Sciences* 14, no. 2 (2014): 97-103.

[28] Nyers, Jozsef, Slavica Tomic, and Arpad Nyers. "Economic optimum of thermal insulating layer for external wall of brick." *Acta Polytechnica Hungarica* 11, no. 7 (2014): 209-222.

[29] Fertelli, Ahmet. "Determination of optimum insulation thickness for different building walls in Turkey." *Transactions of FAMENA* 37, no. 2 (2013): 103-113.

[30] Kayfeci, Muhammet, Ali Keçebaş, and Engin Gedik. "Determination of optimum insulation thickness of external walls with two different methods in cooling applications." *Applied thermal engineering* 50, no. 1 (2013): 217-224.

[31] Ekici, Betul Bektas, Ayca Aytac Gulten, and U. Teoman Aksoy. "A study on the optimum insulation thicknesses of various types of external walls with respect to different materials, fuels and climate zones in Turkey." *Applied Energy* 92 (2012): 211-217.

[32] Mishra, Subhash, J. A. Usmani, and Sanjeev Varshney. "Optimum insulation thickness of the external walls and roof for different degree-days region." *International Journal of Engineering Research & Technology (IJERT)* 7, no. 1 (2012).

[33] Mishra, Subhash, J. A. Usmani, and Sanjeev Varshney. "Energy saving analysis in building walls through thermal insulation system." *International Journal of Engineering Research and Applications* 2, no. 5 (2012): 128-135.

[34] Daouas, Naouel. "A study on optimum insulation thickness in walls and energy savings in Tunisian buildings based on analytical calculation of cooling and heating transmission loads." *Applied Energy* 88, no. 1 (2011): 156-164.

[35] Zhu, Panyu, Volker Huckemann, and M. Norbert Fisch. "The optimum thickness and energy saving potential of external wall insulation in different climate zones of China." *Procedia Engineering* 21 (2011): 608-616.

[36] Agra, Özden, S. özgür Atayilmaz, Hakan Demir, and Ismail Teke. "Environmental impact of optimum insulation thickness in buildings." In *World Renewable Energy Congress-Sweden; 8-13 May; 2011; Linköping; Sweden*, no. 057, (2011): 1813-1820. Linköping University Electronic Press.

[37] Ramin, Hadi, Pedram Hanafizadeh, and Mohammad Ali Akhavan Behabadi. "Thermal, Economical and Environmental Optimization of Insulation Thickness in Residential Building's Wall." *Modares Mechanical Engineering* 16, no. 13 (2016): 252-255.

[38] Saadatian, Seyedeh Shiva, Fausto Freire, and Nuno Simões. "Comparative Life-Cycle Analysis of Insulation Materials in a Dwelling, Addressing Alternative Heating Systems and Life Spans." *Journal of Clean Energy Technologies* 4, no. 6 (2016): 462-465.

[39] Arıcı, Müslüm, and Hasan Karabay. "Determination of optimum thickness of double-glazed windows for the climatic regions of Turkey." *Energy and Buildings* 42, no. 10 (2010): 1773-1778.

[40] Bolattürk, Ali. "Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey." *Applied thermal engineering* 26, no. 11-12 (2006): 1301-1309.

[41] Bolattürk, Ali. "Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey." *Building and environment* 43, no. 6 (2008): 1055-1064.

[42] Sisman, Nuri, Emin Kahya, Nil Aras, and Haydar Aras. "Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey's different degree-day regions." *Energy Policy* 35, no. 10 (2007): 5151-5155.

[43] Dombaycı, Ö. Altan, Mustafa Gölcü, and Yaşar Pancar. "Optimization of insulation thickness for external walls using different energy-sources." *Applied Energy* 83, no. 9 (2006): 921-928.

[44] Hasan, Afif. "Optimizing insulation thickness for buildings using life cycle cost." *Applied energy* 63, no. 2 (1999): 115-124.

[45] Kaynakli, Ömer. "Optimum Thermal Insulation Thicknesses and Payback Periods for Building Walls in Turkey." *Isi Bilimi Ve Teknigi Dergisi-Journal of Thermal Science and Technology* 33, no. 2 (2013): 45-55.

[46] Jafri, S. Ali Husain, P. K. Bharti, and M. Jamil Ahmad. " Opimum insulation thickness for building envelope - A review." *International Journal of Research in Engineering and Technology* 4, no.9 (2015).

[47] Liu, Xiangwei, Youming Chen, Hua Ge, Paul Fazio, and Guojie Chen. "Numerical investigation for thermal performance of exterior walls of residential buildings with moisture transfer in hot summer and cold winter zone of China." *Energy and Buildings* 93 (2015): 259-268.

[48] Ozel, Meral. "Thermal performance and optimum insulation thickness of building walls with different structure materials." *Applied Thermal Engineering* 31, no. 17-18 (2011): 3854-3863.

[49] Ozel, Meral. "Cost analysis for optimum thicknesses and environmental impacts of different insulation materials." *Energy and Buildings* 49 (2012): 552-559.

[50] Rahul Jain and R.C. Gupta. "Optimum insulation thickness for reefer truck." *International Journal of Thermal Technologies* 2, no. 1 (2012): 141-147.

[51] Al-Sanea, Sami A., M. F. Zedan, Saleh A. Al-Ajlan, and Atif S. Abdul Hadi. "Heat transfer characteristics and optimum insulation thickness for cavity walls." *Journal of Thermal Envelope and Building Science* 26, no. 3 (2003): 285-307.

[52] Abdul Talib Din, Norzawahir Mohd Hafiz, and Anika Zafiah Mohd Rus. "Exploration to Find Green Building Materials from Recycled Solid Wastes." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 47, no. 1 (2018): 35-44.

[53] Suhaila Sahat, Nor Farah Atiqah Ahmad, Siti Noor Aiin Mohd Razali, Masiri Kaamin, Mardiha Mokhtar, Nor Baizura Hamid, Norhayati Nyadiman. "Effectiveness of Corn Cob as a Thermal Isolation Material." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 50, no. 1 (2018): 10-15.

[54] Ahmad, Eball H. "Cost analysis and thickness optimization of thermal insulation materials used in residential buildings in Saudi Arabia." In *Proceedings of the 6th Saudi Engineering Conference, Dhahran, Saudi Arabia* (2002): 14-17.