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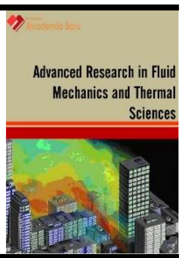

A Study on Energy Performance and Optimum Thickness of Thermal Insulation for Building in Different Climatic Regions in Sudan

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ABSTRACT

The energy performance and optimum thickness of thermal insulation for buildings under Sudan climate regions was studied in this paper. Energy consumption principally of the building section represents a large section of the total energy consumption in Sudan. It is very important to mention that about more than 55% of total energy has been consumed in the buildings for heating and cooling purposes. The residential sector consumes about 56.7% from the total electrical energy consumption in Sudan. Heating/Cooling degree days method (HDD/CDD) with the life cycle cost analysis (LCCA) and an approach for insulation materials thickness optimization, energy saving, and payback period together with the MATLAB software are used in this study to calculate the optimum thermal insulation thickness for four selected cities in Sudan namely Khartoum, Dongola, Port Sudan, and Nyala, where an each city of them have a different climatic conditions. The optimum insulation thickness calculated for an external wall applied three different insulation materials which are Extruded polystyrene (XPS), Expanded polystyrene (EPS), and Glass wool (GW). These materials are applied for three different types of walls which are fired clay bricks, perforated red bricks, and cement hollow block. The results show that the optimum insulation thicknesses vary from 6 to 41 mm depending on the selected city. The energy cost savings and payback periods due to the optimum insulation thickness were determined for each selected city with the three insulation materials. The range of the annual energy cost savings is found to be between 0.4 to13.1 \$/m^2.

Keywords:
Optimum thermal insulation thickness; Insulation materials; Life cycle cost

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1. Introduction

Heating and cooling loads of buildings are generally due to the heat transferred across the building in summer from external building to its internal. This trend is reflected in winter due to the temperature differences between the external and internal walls of the building. Increasing in global warming issues, many products have been developed as one way to maintain the comfortability and to control the temperature in a building. To maintain and control the thermal comfort in the building especially during summer time, the heat transfer into the building should be reduced. The air conditioner and fan are some of the mediums used to control thermal comfort in building [1]. The insulation performance of the external walls of a building is a critical factor for the energy consumption of air conditioning system. Thermal insulation considers one of the solutions to reduce the heat loss from the buildings sectors, where insulation thickness is a significant parameter. The insulation technique has developed significantly in many forms and types. But, the use of the thermal insulation in Sudan is still little. Energy consumption principally of the building section, are represents a large section of the total energy consumption in Sudan. It was very important to mention that about more than 55% of total energy has been consumed in the buildings for heating and cooling purposes. This is of course due to the hot climate in Sudan beside that, the majority of buildings in the country do not have insulation. The residential sector consumes about (56.7%) from the total electrical energy consumption in Sudan [2]. The Increases in energy consumption in building in Sudan is big problem facing the Energy Management and Development and Sudanese Electricity Distribution Company. Also, the increases in fuel and electricity price sharply increase the cost of energy production. In addition to the problem of environmental pollution which comes from using the fuels in cooling systems.

There is 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 technique for analysis. Aynur and Figen [3] used the degree-days method to calculate the optimum insulation thickness of the external wall for four cities from four climate zones of Turkey, energy savings over a lifetime of 10 years and payback periods for the five different energy types and four different insulation materials applied externally on walls. Cenker A. and Uğur A [4] determined optimum insulation thickness for the exterior walls of buildings in Turkey based on different materials, energy sources and climate regions for different four cities in Turkey, a life-cycle cost analysis is presented to show the optimum insulation thickness, energy savings over a lifetime of 15 years and payback periods for six different fuels and six insulation materials, the studies used the degree-days method. Ali Bolatturk [5-6] determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey, the calculated based on both annual heating and cooling loads. The selection of the optimum insulation thickness depended on the heating and cooling loads the studies used the degree-days method to calculate these loads. Betul Bektas Ekici *et al.,* [7] calculated the optimum insulation thicknesses, energy savings and payback periods for four cities from different climate zones, by the Turkish Thermal Insulation Standard. Okan [8] used economical analyses to determined optimum insulation thicknesses for exterior walls of buildings with different masses in five different cities in different climate regions in Turkey and insulation thicknesses of exterior walls of sample buildings were calculated by using optimization and the degree-days method. Nuri Alpay Kurekci [9] determined the optimum insulation thicknesses in Turkey’s 81 provincial centres, the calculations were made on the basis of four different fuels (natural gas, coal, fuel oil and liquefied petroleum gas) and five different insulation materials (extruded polystyrene, expanded polystyrene, glass wool, rock wool and polyurethane). There are three different cases considered in study: buildings heated but not cooled,

cooled but not heated, and both heated and cooled, optimum insulation thicknesses in accordance with each case had been calculated. M. Morsy*et al.,* [10] Studied the effect of thermal insulation on building thermal comfort and energy consumption in Egypt. Nuri Sismana*et al.,* [11] determined the optimum insulation thicknesses of the external walls and roof (ceiling) for different degree-day regions of Turkey. In all previous studies determination of optimum thermal insulation thickness for energy saving for building walls studied in many countries mentioned above in literature reviews except in Sudan there's no study studied this topic. Therefore, this study is proposed to determination of optimum thermal insulation thickness for energy saving for different building walls and different climate of four cites in Sudan named Khartoum, Nyala, Dongola, and Port Sudan using the degree day's technique and life cycle cost analysis.

It is very important to properly select the type of insulator, applying insulation at optimum thickness considering investment and operating costs. Heating/Cooling degree days method (HDD/CDD) with the life cycle cost analysis (LCCA) and an approach for insulation materials thickness optimization, energy saving, and payback period together with the MATLAB software are used in this study to calculate the heating and cooling loads which are considered as one of input parameters used in the optimum insulation thickness calculation. The present research employed the (CDD) technique to determine the optimum insulation thickness, energy saving, and payback period after the insulation materials had been applied to the exterior walls of buildings. This was done for four selected cities in Sudan namely Khartoum, Dongola, Port Sudan, and Nyala where each city of them have different climatic conditions.

The optimum insulation thickness calculated for an external wall with three different insulation materials which are Extruded polystyrene (XPS), Expanded polystyrene (EPS), and Glass wool (GW). These materials are applied for three different wall types which are fired clay bricks, perforated red bricks, and cement hollow block.

2. Energy Consumption in Sudan

The energy consumption in Sudan is distributed among five main sectors namely residential, commercial, industrial, governmental and agriculture. Figure 1 shows the distribution of the energy consumption in Sudan for these sectors in 2016 [2]. From this figure, it can be seen that an increase in the energy demand especially in the residential sector.

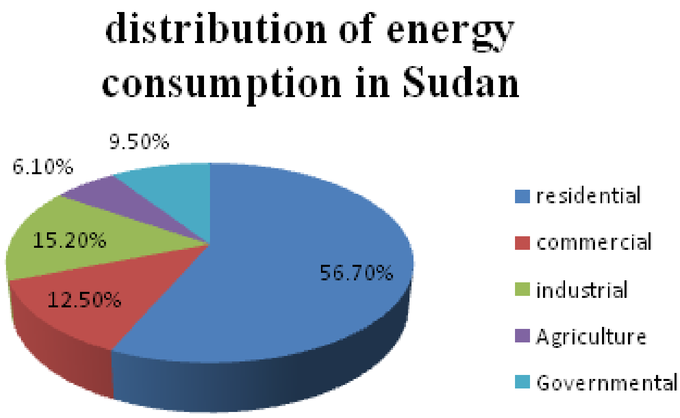

Fig. 1. Percentage of the energy consumption in Sudan in 2016

2.1 Building Materials and Structure of External Walls

There are many types of building materials used for construction in Sudan, the most common construction materials applied for external walls of buildings in Sudan inclusive of fired clay bricks, perforated red bricks, and cement hollow block compressed earth block, as shown in Table 1. The insulated composite wall consists of 20 mm thick layer of cement internal plaster and external plaster, 200 mm-thick layer of each building material.

Table 1
Physical and thermal properties of building construction materials of the external wall [10]

	Thickness, m	Thermal conductivity, (W/m °C)	R, (m^2K/W)
Fired clay bricks	0.2	0.72	0.286
Perforated Red brick	0.2	0.46	0.435
Cement hollow block	0.2	1.7	0.118
Internal plaster	0.02	0.72	0.023
External plaster	0.02	0.72	0.023
R_i			0.167
R_o	For Khartoum, Port Sudan, Dongola		0.0234
R_o	For Nyala		0.029
R_{wt}			
Wall 1	Khartoum, Port Sudan, Dongola		0.5224
Wall 2	Khartoum, Port Sudan, Dongola		0.6714
Wall 3	Khartoum, Port Sudan, Dongola		0.3544
Wall 1	Nyala		0.528
Wall 2	Nyala		0.677
Wall 3	Nyala		0.36

3. Heating and Cooling Degree Days Method (HDD/CDD)

The method of Heating/Cooling degree days (HDD/CDD) is used in the present study to calculate the loads of heating and cooling which are considered as one of the most important input parameters used to determine the optimum insulation thickness. The present paper employed the (CDD) technique to determine the optimum insulation thickness, energy saving, and payback period after the insulation materials had been applied to the exterior walls of buildings. This was done for four selected cities in Sudan namely Khartoum, Dongola, Port Sudan, and Nyala where each city of them have a different climatic condition. To compute (HDD) and (CDD) in the present paper , the average daily outdoor temperature for year 2016 related to these selected four cities is used [12]. The HDD is calculated by assuming the base temperature is 18°C for heating, while the CDD is calculated by assuming it as 26°C. Both the HDD and CDD are determined and illustrated in Table 2. Three different insulation materials are selected including extruded polystyrene (XPS), expanded polystyrene (EPS), and glass wool (GW), and the parameters used in the calculation of the optimum insulation thickness are given in Table 3.

Table 2
Climate zones of the four selected cities

City	Longitude, °	Latitude, °	Altitude, m a.s.l	Heating Degree-days (°C-days)	Cooling Degree-days (°C-days)
Khartoum	32° 33\ E	15° 36\ N	382	3.75	1945
Dongola	30° 29\ E	19° 10\ N	226	79.5	1827
Port Sudan	37° 13\ E	19° 35\ N	3	0	1759
Nyala	24° 53\ E	12° 03\ N	658	5.05	1123

Table 3
Insulation material parameters

Insulation material	Thermal conductivity (W/m °C)	Cost ($/m^3)
Extruded polystyrene (XPS)	0.031	200
Expanded polystyrene (EPS)	0.039	160
Glass wool (GW)	0.040	110

It is useful to mention that, buildings lose heat through external wall surface, window, ceiling and air infiltration [3-8, 11, 13-14]. The heat loss from the unit surface of the external wall is computed from:

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

where
U: The overall heat transfer coefficient
T_b: The base temperature
T_o: The mean daily temperature.

The annual heat losses and gains occurring in the unit surface are computed by using the overall heat transfer coefficient(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.

The heating degree days (HDD) is the summation of the temperatures below the temperature of a certain basis, or the absolute value (positive) of the difference between the average daily temperature and the base temperature. It can be calculated mathematically as follows.

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

By the same way, (CDD) can be calculated mathematically as follows.

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

The annual cooling load is calculated as follows.

$$E_{A,C} = \frac{86400 \times CDD \times U}{COP} \tag{6}$$

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

$$U = \frac{1}{R_i + R_W + R_{ins} + R_O} \tag{7}$$

where (R_i) is the inside air film thermal resistance, (R_w) is the total thermal resistance of the wall without the insulation, (R_{ins}) is the insulation layer thermal resistance and (R_o) is the thermal resistance of outside air film. If the combined heat transfers coefficients at the inner and outer surfaces are taken to be (6 W/m^2 K). The R_i was determined as (0.167 m^2 K/W), while R_o was computed by the following equation [2].

$$R_o = \frac{1}{5.8+4.1\times V} \tag{8}$$

where (V) is the air velocity in (m/s)

The insulation layer thermal resistance (R_{ins}) is given by

$$R_{ins} = \frac{x}{k} \tag{9}$$

where(x) is the thickness of the insulation layer, and (k) is the insulation material thermal conductivity. Let us define

$$R_{wt} = R_i + R_w + R_o \tag{10}$$

where (R_{wt}) is the total thermal resistance of the wall excluding the resistance of the insulation layer. Then Eq. (7) can be rewritten as follows.

$$U = \frac{1}{R_{wt}+R_{ins}} \tag{11}$$

The annual energy need for cooling ($E_{A,C}$) is given by

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

where (COP) is the cooling system coefficient of performance

3.1 Life-Cycle Cost Analysis (LCCA) and the Optimization of Insulation Thickness

The life-cycle cost analysis (LCCA) should be employed when determining the optimum insulation thickness. It involves the analysis of the system costs or a component over its entire lifetime. The (LCCA) is used in the present study to compute the total heating cost over the lifetime of the insulation material which was taken as 20 years. The parameters used in the life-cycle cost analysis (LCCA) calculation are given in Table 4. The total cooling cost is calculated together with the present-worth factor (PWF) for the lifetime of N years. The (PWF) is mainly influenced by inflation rate (g) and the interest rate (i). According to the interest and inflation rates, (PWF) is defined as follows [5-7].

$$PWF = \frac{(1+r)^N-1}{r\times(1+r)^N} \tag{13}$$

The above relation can be used under the following condition,

If i > g, then

$$r = \frac{i-g}{1+g} \tag{14}$$

or if i < g, then

$$r = \frac{g-i}{1+i} \tag{15}$$

where (N) is the lifetime, as mentioned earlier it is estimated to be 20 years for this study.

If i = g then, (PWF) is defined as

$$PWF = \frac{N}{1+i} \tag{16}$$

3.2 Annual Energy Cost and Computation of The Optimum Insulation Thickness

The cost of annual energy for unit surface for cooling ($C_{A,C}$) is calculated by using the following equation.

$$C_{A,C} = \frac{86400 \times CDD \times C_e}{\left(R_{wt} + \frac{x}{k}\right) \times COP} \tag{17}$$

where (C_e) is the electricity cost

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

$$C_{ins} = C_i \times x \tag{18}$$

where (C_i) in $\$/m^3$is the insulation material cost.

The total cooling cost of the insulated building is given by

$$C_{t,c} = C_{A,c} \times PWF + C_i \times x \tag{19}$$

The optimum insulation thickness that minimizes the total cooling cost is determined by using the following equation.

$$x_{opt,C} = 293.94 \times \left(\frac{CDD \times C_e \times PWF \times k}{C_i \times COP}\right)^{1/2} - k \times R_{wt} \tag{20}$$

3.3 Energy Cost Saving Analysis

For building exterior walls, the annual cost of energy saving per unit area is the difference between the annual total cost of energy per unit area of these walls without insulation and the annual total cost of energy per unit area for insulated walls. The relationship is presented by the following equation [9, 15-17].

For the exterior walls of the building, the annual cost of cooling energy saving per unit area ($E_{cs,c}$) , ($\$/m^2$) is defined by

$$E_{CS,c} = C_c - C_{t,c} \tag{21}$$

where, (Cc) is the building exterior walls annual total cost of cooling per unit area for non-insulated walls, ($\$/m^2$), while ($C_{t,C}$) is the building exterior walls annual total cost of cooling per unit area for insulated walls, ($\$/m^2$).

The energy saving can be expressed as a present ratio by the following equation.

$$\frac{E_{CS,H,c}}{C_{H,C}} \times 100 \quad (22)$$

3.4 Payback Period

The payback period (years) indicates the number of years which are necessary to recover the investment. It can be calculated by dividing the total insulation cost, by the yearly energy cost savings [8].

$$PP_c = \frac{C_{ins}}{E_{CS,c}} \quad (23)$$

Table 4
Parameters used in the calculations

Interest rate (i)	13.5%
Inflation rate (g)	35%
Lifetime (LT)	20 years
Present worth factor (PWF)	5
Cost of electricity C_e	0.089 $/kWh
COP	2.5

4. Results and Discussion

The cooling and heating degree day (CDD/HDD) calculated at two different base temperatures which are (T_b=26 °C for CDD), and (T_b=18°C for HDD). Table 2 summarizes the results of the cooling and heating degree day (CDD/HDD) of these two base temperatures and average temperatures for four selected cities in Sudan. It can be seen from these values, there is an inverse relationship between the CDD/HDD and the value of the base temperature. Therefore, the latter increases when the corresponding value of CDD/HDD decreases. From the values of the base and average temperatures, it can be seen that the north region of Sudan (Khartoum and Dongola) have the highest values of the annual cooling degree days (1945, 1827) and a relatively low value of the annual heating degree days (3.75, 79.5).This indicates that the buildings located in this region consume a high energy in the cooling seasons. From the other hand, the west region of Sudan like Nyala city for example has a lower value of the cooling degree days.

From economical point of view, the best value of the insulation thickness is the thickness is the one corresponds to the minimum point of the total cost, this value is known as the optimum insulation thickness. Figure 2 to 5 clearly revealed that the optimum insulation thickness for extruded polystyrene (XPS) while using Perforated Red brick, are 15.3, 14.2, 13.5 and 6 mm for Khartoum, Dongola, Port Sudan, and Nyala respectively. It also can be observed that, the insulation cost increases linearly, while the energy cost decreases with increasing of the insulation thickness. Also, it can be seen that the optimum insulation thickness value is the minimum point of the total cost.

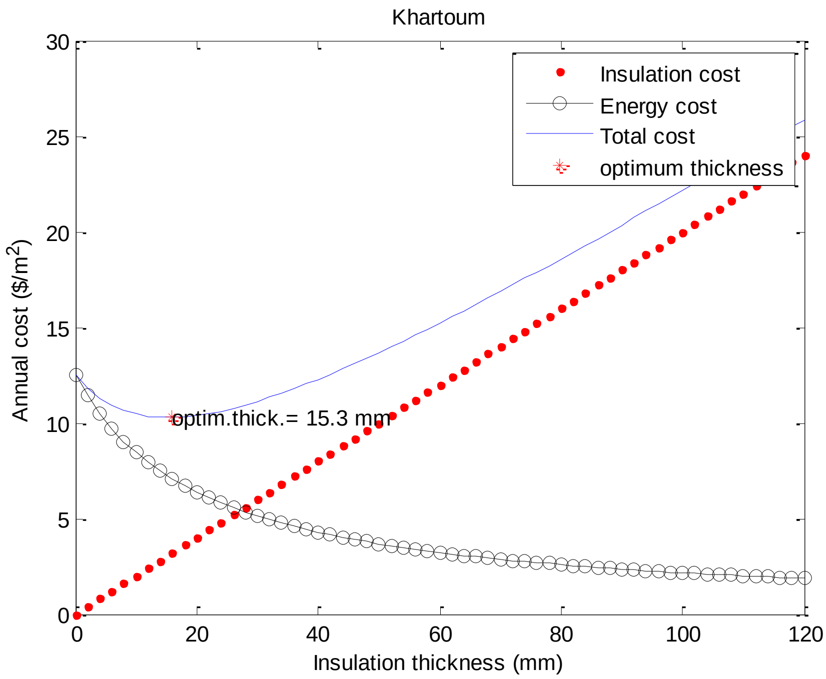

Fig. 2. Effect of the insulation thickness of extruded polystyrene (XPS) on the total cost in case cooling energy requirement used perforated red brick in Khartoum

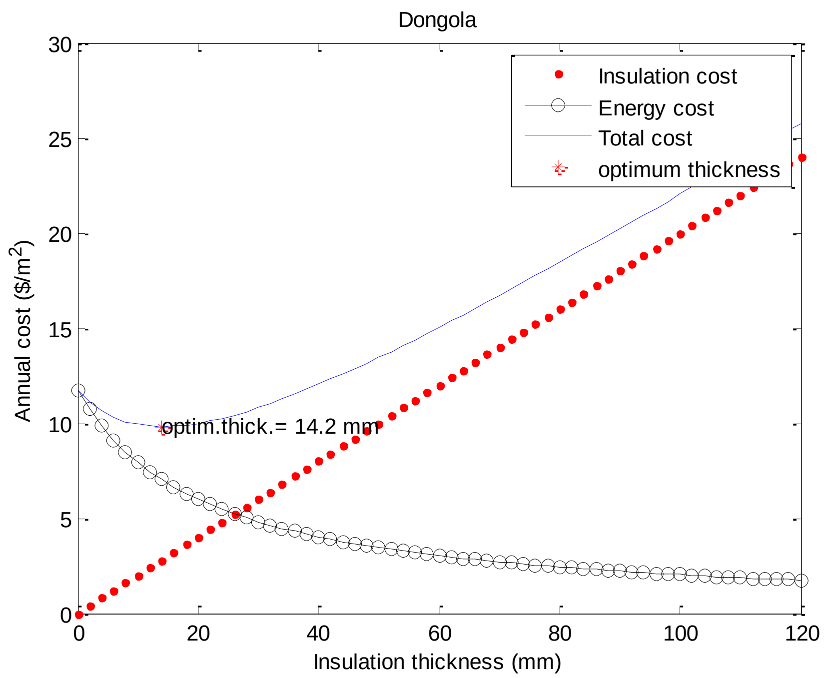

Fig. 3. Effect of the insulation thickness of extruded polystyrene (XPS) on the total cost in case cooling energy requirement used perforated red brick in Dongola

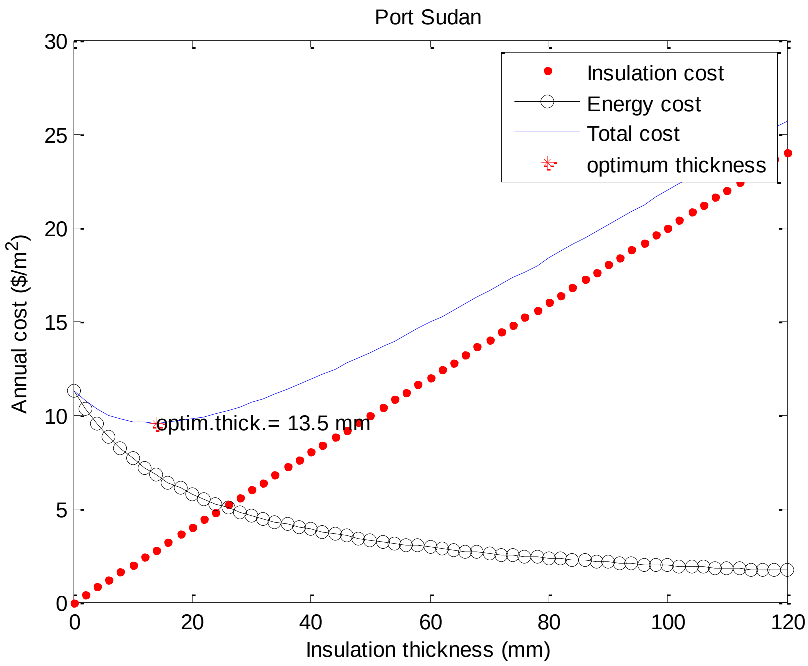

Fig. 4. Effect of the insulation thickness of extruded polystyrene (XPS) on the total cost in case cooling energy requirement used perforated red brick in Port Sudan

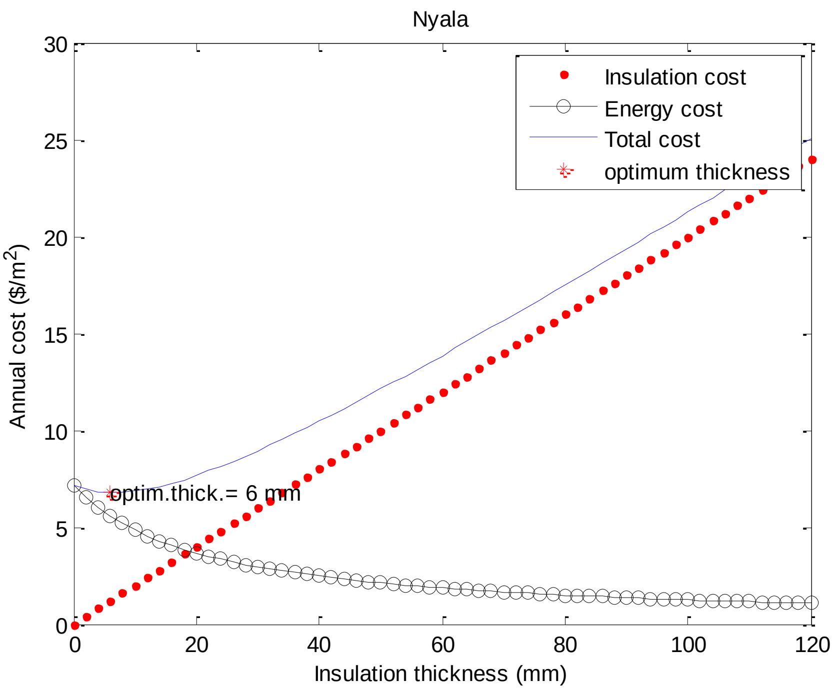

Fig. 5. Effect of the insulation thickness of extruded polystyrene (XPS) on the total cost in case cooling energy requirement used perforated red brick in Nyala

Figure 6 to 9 illustrate the comparison of the annual energy savings of all insulation materials in the case of the cooling requirement for Khartoum, Dongola, Port Sudan, and Nyala respectively when the selected fired clay bricks were used. It can be seen from these figures that; the annual energy cost savings increases up to the point corresponding to the optimum insulation thickness values. Then, it gradually decreases after this point. It can be concluded that, the continuous increase of the insulation thickness after the optimum thickness also increase the total cost and reduces the economic benefits. Energy cost savings corresponding to the optimum thickness of all insulation materials is about are 2.2, 1.9, 1.8 and 0.4 with wall type perforated red brick, respectively according to the extruded polystyrene (XPS). The payback period (years) are 1.43, 1.5, 1.6 and 3.1 with the wall type perforated red brick respectively according to the Extruded polystyrene (XPS).

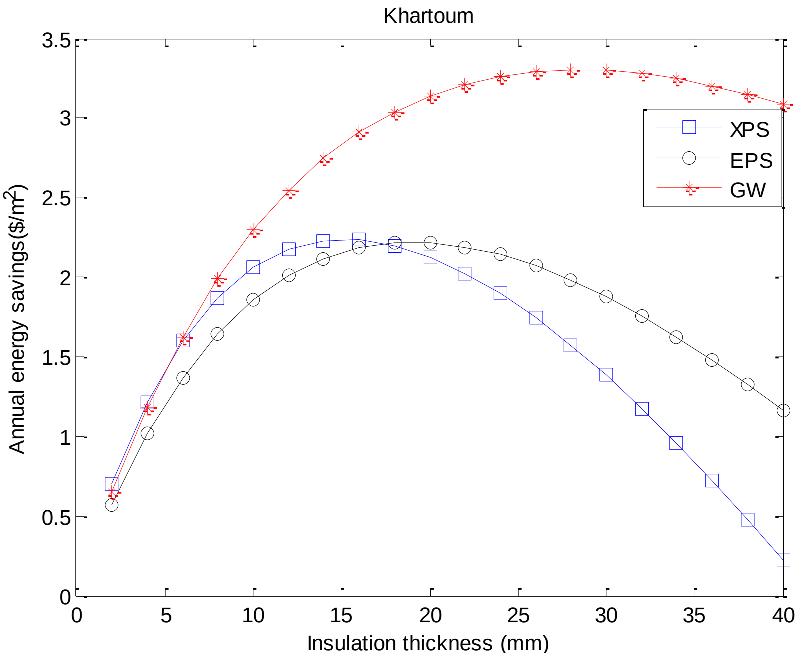

Fig. 6. Comparison of the annual energy savings of all insulation materials in the case of the cooling requirement for selected fired clay bricks in Khartoum

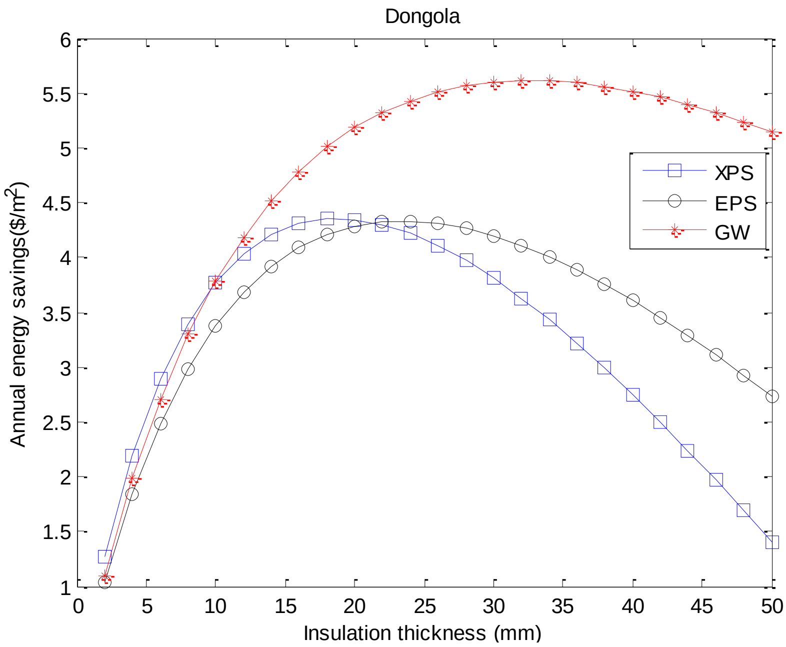

Fig. 7. Comparison of the annual energy savings of all insulation materials in the case of the cooling requirement for selected fired clay bricks in Dongola

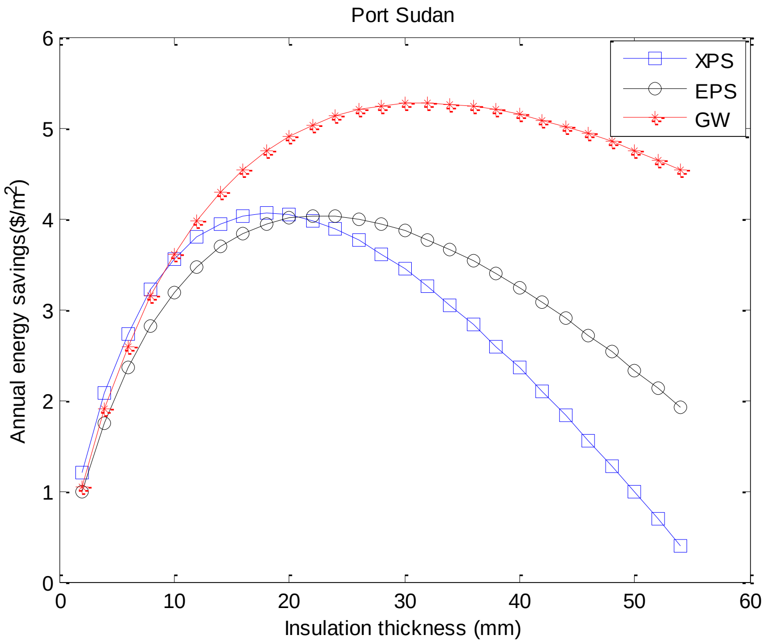

Fig. 8. Comparison of the annual energy savings of all insulation materials in the case of the cooling requirement for selected fired clay bricks in Port Sudan

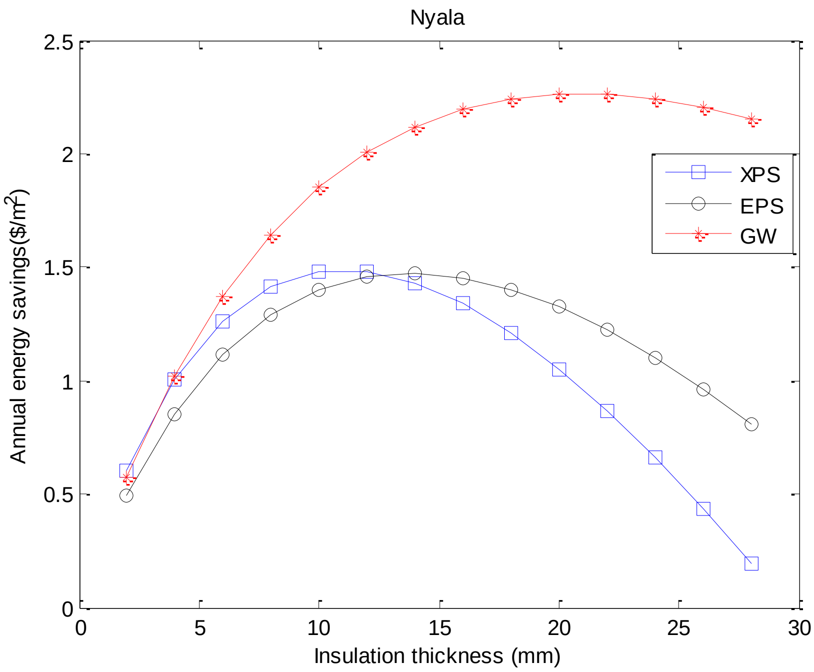

Fig. 9. Comparison of the annual energy savings of all insulation materials in the case of the cooling requirement for selected fired clay bricks in Nyala

The result of calculations for Khartoum, Dongola, Port Sudan, and Nyala cites were shown respectively in Table 5, 6, 7 and 8 with the optimum insulation thickness, energy savings ($\$/m^2$) and the payback period (years).

Table 5 - 7 show that the optimum insulation thickness in Khartoum city varies from 15.3 mm when using extruded polystyrene (XPS) to 41.1 mm when using the glass wool (GW) as an insulating

material. While in Dongola city, it varies from 14.2 mm when using extruded polystyrene (XPS) to 39.4 mm when using the glass wool (GW)as an insulating material. With respect to Port Sudan and Nyala cities, they vary respectively between 13.5 mm and 6.4 mm by using extruded polystyrene (XPS) as an insulating material. While, they vary respectively between 38.4 mm and 27.6 mm by using the glass wool (GW) as an insulating material. Moreover, it can be seen also from these tables that the annual energy cost savings vary between 2.2 to 13.1 $/m^{2}in Khartoum, 1.9 to 12 $/m^2 in Dongola, 1.7 to 11.4 $/m^2 in Port Sudan and 0.4 to 5.8 $/m^{2}in Nyala depending on the insulation material. According to these results, it can be concluded that the highest energy cost saving was reached by using the glass wool (GW) as an insulating material, while the lowest one was reached by using an expanded polystyrene (EPS) as it with respect to the payback periods, they vary between 0.4 to 1.5, 0.4 to 1.5, 0.4 to 1.6, and 0.5 to 3.3 years for Khartoum, Dongola, Port Sudan and Nyala respectively.

Table 5
Optimum insulation thickness, annual energy savings and the payback periods of Khartoum city for various insulation materials and different wall types

Wall type	Khartoum Insulation material type Extruded polystyrene (XPS)	Expanded polystyrene (EPS)	Glass wool (GW)
Optimum insulation thickness (mm)			
Fired clay bricks	19.9	24.9	34.4
Perforated Red brick	15.3	19.1	28.4
Cement hollow block	25.1	31.4	41.1
Annual energy savings ($/m^2)			
Fired clay bricks	4.9	4.9	6.2
Perforated Red brick	2.2	2.2	3.3
Cement hollow block	11.5	11.4	13.1
Payback period (years)			
Fired clay bricks	0.8	0.8	0.6
Perforated Red brick	1.4	1.5	0.9
Cement hollow block	0.5	0.5	0.4

Table 6
Optimum insulation thickness, annual energy savings and the payback periods of Dongola city for various insulation materials and different wall types

Wall type	Dongola Insulation material type Extruded polystyrene (XPS)	Expanded polystyrene (EPS)	Glass wool (GW)
Optimum insulation thickness (mm)			
Fired clay bricks	18.8	23.5	32.7
Perforated Red brick	14.2	17.7	26.7
Cement hollow block	24	30	39.4
Annual energy savings ($/m^2)			
Fired clay bricks	4.4	4.3	5.6
Perforated Red brick	1.9	1.9	2.9
Cement hollow block	10.7	10.4	12
Payback period (years)			
Fired clay bricks	0.8	0.9	0.6
Perforated Red brick	1.5	1.5	1
Cement hollow block	0.5	0.5	0.4

Table 7
Optimum insulation thickness, annual energy savings and the payback periods of Port Sudan city for various insulation materials and different wall types

Wall type	Port Sudan Insulation material type Extruded polystyrene (XPS)	Expanded polystyrene (EPS)	Glass wool (GW)
Optimum insulation thickness (mm)			
Fired clay bricks	18.1	22.7	31.7
Perforated Red brick	13.5	16.8	25.7
Cement hollow block	23.3	29.2	38.4
Annual energy savings ($/m²)			
Fired clay bricks	4.1	4	5.3
Perforated Red brick	1.8	1.7	2.7
Cement hollow block	9.9	9.9	11.4
Payback period (years)			
Fired clay bricks	0.9	0.9	0.7
Perforated Red brick	1.6	1.5	1.1
Cement hollow block	0.5	0.5	0.4

Table 8
Optimum insulation thickness, annual energy savings and the payback periods of Nyala city for various insulation materials and different wall types

Wall type	Nyala Insulation material type Extruded polystyrene (XPS)	Expanded polystyrene (EPS)	Glass wool (GW)
Optimum insulation thickness (mm)			
Fired clay bricks	11	13.8	20.9
Perforated Red brick	6.4	8	14.9
Cement hollow block	16.3	20.3	27.6
Annual energy savings ($/m²)			
Fired clay bricks	1.5	1.5	2.3
Perforated Red brick	0.4	0.4	0.9
Cement hollow block	4.7	4.7	5.8
Payback period (years)			
Fired clay bricks	1.6	1.5	1
Perforated Red brick	3.1	3.3	1.7
Cement hollow block	0.7	0.7	0.5

The optimum insulation thickness for the external wall in Khartoum, Dongola, Port Sudan and Nyala were 15.3, 14.2, 13.5 and 6.4 mm respectively for the extruded polystyrene (XPS) material used perforated red brick, 19.1, 17.7, 16.8 and 8 mm respectively for the expanded polystyrene (EPS) material used perforated red brick and 28.4, 26.7, 25.7, and 14.9 mm respectively for the glass wool (GW) material used perforated red brick. The difference between the optimum insulation thickness values for the external wall obtained in Khartoum, Dongola, Port Sudan and Nyala is due to the variation in the cooling degree day (CDD) which is calculated in Table 6. This value is 1945, 1827, 1759 and 1123 for Khartoum, Dongola, Port Sudan, and Nyala respectively. The results show that the optimum insulation thicknesses vary between 6.4 and 41.1 mm depending on the city. Also, it can be seen from Table 5, 6, 7 and 8 that the energy cost savings vary between 0.4 and 13.1 $\$/m^2$ depending on the insulation material. However, it can be concluded that the highest optimum insulation thicknesses and energy cost savings are reached by using the glass wool (GW) as an insulating material in Khartoum. While, the lowest value is obtained by using the Extruded polystyrene (XPS) as an insulating material in Nyala.

Furthermore, it can be concluded that the annual energy cost savings are 48.3% in Khartoum, 47 % in Dongola, 46.2% in Port Sudan, and 35.1% in Nyala by using the extruded polystyrene materials. While, they become 55.3% in Khartoum, 54.1 % in Dongola, 53.3% in Port Sudan, and 43.2% in Nyala by using the glass wool materials.

Figure 10 represents the relationship between the optimum insulation thickness and the cooling degree days (CDD) of three different insulation materials for all selected cities. It can be observed that, the optimum insulation thickness of external walls increases as the cooling degree days (CDD) values increase.

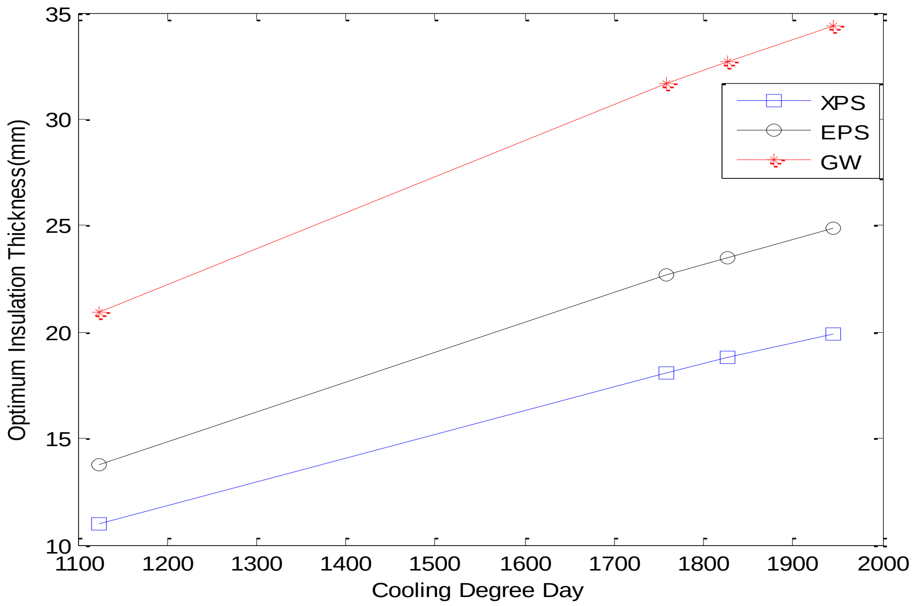

Fig. 10. Optimum insulation thicknesses of external walls versus cooling degree days (CDD) values for three insulation materials for all considered cities

5. Conclusions

In this paper, the optimum insulation thickness for the external wall surface of building was calculated by using the heating/cooling degree days method together with the life cycle cost analysis (LCCA) and an approach for the insulation materials thickness optimization, energy saving, and payback period by using MATLAB software, for four selected cities in Sudan namely Khartoum, Dongola, Port Sudan, and Nyala. Extruded polystyrene (XPS), Expanded polystyrene (EPS), and Glass wool (GW) were used as an insulation material for residential buildings cooling. In addition to them, fired clay bricks, perforated red brick, and cement hollow block were applied as structures wall types in these buildings. The results show that the optimum insulation thicknesses vary between 6.4 and 41.1 mm depending on the city. The optimum insulation thickness for the external wall in Khartoum, Dongola, Port Sudan and Nyala were 15.3, 14.2, 13.5 and 6.4 mm respectively for the extruded polystyrene (XPS) material used perforated red brick, 19.1, 17.7, 16.8 and 8 mm respectively for the expanded polystyrene (EPS) material used perforated red brick and 28.4, 26.7, 25.7, and 14.9 mm respectively for the glass wool (GW) material used perforated red brick. It can be concluded that the highest optimum insulation thicknesses and energy cost savings are reached by using the glass wool (GW) as an insulating material in Khartoum. While, the lowest value is obtained by using the Extruded polystyrene (XPS) as an insulating material in Nyala. Also, the results explain that the energy cost savings vary between 0.4 and 13.1 $/m^2 depending on the insulation material. Furthermore, it can be concluded that the annual energy cost savings are 48.3% in Khartoum, 47 % in Dongola, 46.2% in Port Sudan, and 35.1% in Nyala by using the extruded polystyrene materials. While, they become 55.3% in Khartoum, 54.1% in Dongola, 53.3% in Port Sudan, and 43.2% in Nyala by using the glass wool materials.

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