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Determination of Optimum Insulation Thickness for Building Walls in Iran Using Life Cycle Cost Analysis

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Abstract

Air-Conditioning (AC) systems are responsible for a considerable portion of energy consumption in buildings located in high cooling load requiring regions of Iran. In addition, the heat flow through the buildings' external walls plays a major role in cooling load estimations for the country's hot regions. Therefore, the application of insulation materials in external walls has gained more interest in recent years. In the present research, a systematic approach to optimize the insulation material thickness has been developed and applied to those regions in Iran which require high cooling load, namely Bandar abbas and Bushehr, through deploying life cycle cost analysis. Moreover, a correlation between optimum thickness and thermal conductivity of insulation materials has been recommended for the buildings located in the above-mentioned hot regions of the country. The study has showed that the relationship between optimum insulation thickness and thermal conductivity has a non-linear trend and obeys a polynomial function.

Keywords: Building Walls, Insulation Material, Optimum Thickness, Thermal Conductivity.

1. Introduction

Providing sustainable energy supply is considered one of the major tasks of governments. Most of energy comes from the fossil fuels which should be spared due to limited resources available and their consequent environmental pollution. Building sectors are responsible for about 40% of the world wide energy consumption [1]. In the building section itself, the most consuming part is Air-Conditioning (AC) systems with about 50% energy consumption. Therefore, the building section as a key energy consuming element needs to be considered for the possible implementation of energy conservation measures.

In addition, AC systems are employed in almost all the offices and commercial buildings of cooling load requiring regions of Iran to provide a comfortable indoor air conditioning. The AC systems are used to cool indoor space and to absorb the heat produced by the internal equipment and people in order to establish comfortable working environments. The AC systems normally operate for considerable hours in a day; therefore, the energy consumption and the cost of these systems are quite significant. As a result, the building sectors in the hot regions of Iran need spend a lot of money on power consumption.

Few methods can be employed to reduce energy consumption in buildings. The heat transfer through building walls constitutes the largest portion of buildings' cooling load and, thus, any kind of reduction in this load could considerably reduce power consumption by the AC systems. Therefore, the implementation of a proper insulation material to achieve cooling load reductions is a decisive task. A proper insulation material could also lead to reductions in the produced emission by power plants.

A proper insulation material is insulation kind of material with optimum thickness, whereby the total cost of insulation and the resulting cooling load reduction cost could be minimized over the lifetime of the building. The cost of insulation material installation can rise in accordance with insulation thickness; on the other hand, the cost of cooling load decreases; therefore, the total cost of insulation and cooling will be minimal if the thickness of insulation is optimum. In other words, insulation thickness beyond the optimum level is not recommended and is not cost effective.

Literature review has indicated that optimum insulation thickness for building walls have already been investigated [2-22]. For instance, the influence of building insulation on cooling load and on AC systems was investigated based on life cycle cost analysis for Adana, Turkey [2]. The study showed that both the initial and the operating costs of the AC systems were reduced significantly for the studied insulation thickness. In another research, emission reduction effects of building walls embedded with optimum insulation thickness and air gaps were explored by Mahlia et al. [4] for Maldives. The study showed that optimal thickness insulation materials which had air gaps of $2\ cm$, $4\ cm$, and $6\ cm$ had the capability of reducing energy consumption and emissions by 65-77%. Climate zones and various fuels were considered to recommend optimum insulation thickness for building walls in Turkey [5]. It was found that optimum insulation thicknesses between 2 and 17 cm are in optimum range based on the fuel type and the city. In another research, heat and moisture transfer model together with lifecycle total cost analysis was considered to study the insulation thickness of the exterior walls [7]. The study showed that the optimum thickness of extruded polystyrene was between 0.053 and 0.069 m and the optimum thickness of expanded polystyrene was between 0.081 and 0.105 m for the studied cities. A dynamic approach was employed to explore the effect of wall positions on optimum insulation thickness for Elazıg, Turkey [8]. Based on the study, 5.5 cm was recommended for extruded polystyrene with south orientation, and 6 cm was proposed for walls with north, east, and west positions. Environmental impacts of thermal insulation thickness in buildings were investigated for Erzurum, Turkey by Comaklı and Yuksel [9]. It was found that 50% reduction in CO_2 emission could be achieved by the means of optimum insulation thickness and other energy saving methods in buildings. Alpay Kurekci [11] investigated the optimum insulation thicknesses for Turkey 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).

The effect of electricity tariff on optimum insulation thickness was studied in Ref. [12]. In another research, the effect of surface reflectivity and the insulation thickness in exterior wall was proposed for Japan [13]. To this end, thermal load calculation software was employed. Exergetic Life Cycle Assessment approach was used to determine the optimum insulation thickness of external walls by Ashouri et al. [15]. Two insulation materials were considered in the analysis, namely Rockwool and Glasswool. The analysis revealed that the optimum insulation thickness are 0.018 m and 0.012 m for Glasswool and Rockwool respectively, with an annual cost saving of 1.6028 $\$/m^2$ and 0.7658 $\$/m^2$.

Derradji et al. [19] investigated the effect of glazing type and the percentage of glazing on the optimum thickness of the insulation in Algerian climate. It was found out that the optimum insulation thickness of expanded polystyrene varies between 1 cm and 2.5 cm. In another report, Kaynakli [20] studied the heating energy requirement and optimum insulation thickness for residential buildings.

In this study, several kinds of insulation materials commercially available in Iran were considered, namely Fibreglass– urethane, Fiberglass (rigid), Urethane (rigid), Perlite, Extruded polystyrene, and Urethane (roof deck)-- and the cost-benefit analysis of optimum thickness for building walls in high cooling load requiring regions of Iran were presented. The study also recommends a correlation between the optimum insulation thickness and thermal conductivity to provide clues regarding the selected insulation materials employed for the building walls of the aforementioned regions during the building designing process.

2. Iran Climate Conditions

The climate condition in a particular region is an important factor for employing AC systems. Iran is a four-season country with a large variation of ambient temperature. Therefore, based on the region of application, the sensible and latent cooling loads are significant factors in the energy consumption of AC systems.

The optimum insulation thickness for cooling load reduction was estimated for those months when temperatures are out of the recommended standards for human thermal comfort. Based on the ASHRAE [23], the recommended indoor air temperature for office buildings in summer is 23-26 $^{\circ}C$.

Fig. 1 illustrates the monthly mean temperature for different regions of the country, namely the northwest, the north, the northeast, central regions, the southwest, and the south of Iran. For this purpose, the latest available data for main cities located in the above-mentioned regions are presented. The studied cities are Tabriz in the northwest, Tehran in the north, Mashhad in the northeast, Esfahan in the center, Bushehr in the southwest and Bandar Abbas in the south.

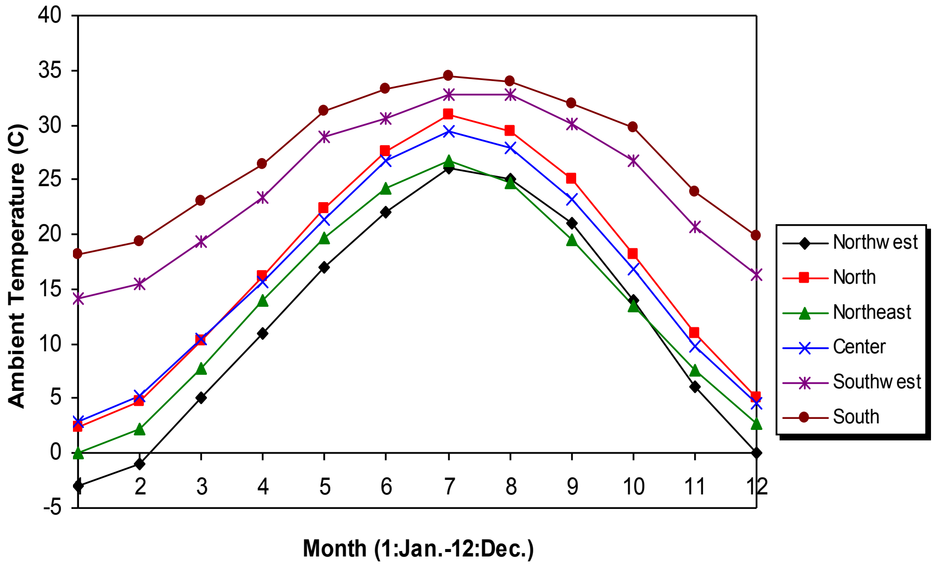

Fig. 1: Monthly mean ambient temperature for different regions of Iran [24]

The monthly mean data are also tabulated in Table 1 for further convenient consideration. As tabulated in Table 1, temperatures in the south and the southwest regions of the country are higher than the recommended standard condition for human thermal comfort during seven and six months of the year, namely April, May, June, July, August, September, and October for the south (Bandar Abbas) and May, June, July, August, September, and October for the southwest (Bushehr). From the latest available data, Bandar Abbas has the maximum monthly mean ambient temperature of 34.4 $^{\circ}C$ in July (see Table 1). Therefore, buildings located in Bandar Abbas and Bushehr, as two cities with high cooling load requirements, were investigated for the present study. In addition, along the design indoor air conditions, the design outdoor air conditions were also required for the calculations. To this end, the design outdoor temperatures recommended in the national standards for Bandar abbas and Bushehr were used.

All the required input data for the calculations are tabulated in Table 2. To conduct the research, the price of insulation materials and thermal conductivities were also needed (Table 3).

Table 1: Monthly mean temperature ($^{\circ}C$) for different regions of Iran [24]

	Northwest (Tabriz)	North (Tehran)	Northeast (Mashhad)	Center (Esfahan)	Southwest (Bushehr)	South (Bandar Abbas)
January	-3	2.4	0.1	2.9	14.1	18.1
February	-1	4.8	2.2	5.3	15.5	19.3
March	5	10.2	7.7	10.5	19.4	23.1
April	11	16.2	13.9	15.6	23.4	**26.4**
May	17	22.3	19.7	21.3	**28.9**	**31.2**
June	22	**27.5**	24.3	**26.7**	**30.6**	**33.3**
July	**26**	**30.9**	**26.7**	**29.4**	**32.8**	**34.4**
August	25	**29.5**	24.7	**27.9**	**32.7**	**34**
September	21	25	19.5	23.2	**30.1**	**32**
October	14	18.2	13.4	16.9	**26.7**	**29.7**
November	6	11	7.6	9.7	20.7	23.9
December	0	5	2.7	4.5	16.3	19.8

Table 2: Analysis required parameters [25]

Description	Value
life cycle period (N)	20 (year)
Resistance of the un-insulated wall (R_{wall})	0.552 ($m^2 {}^{\circ}C/W$)
Unit cost of electricity (mean value) (C_E)	0.0757 ($/kWh)
COP	2.93
Outside-design temperature	40.5 $^{\circ}C$
Inside-design temperature	25 $^{\circ}C$

Table 3: Insulation materials data [3]

Insulation material	Thermal conductivity (k_{ins})	Cost of insulation per cubic meters (C_{ins})	C_{ins} / k_{ins}
Fiber glass-urethane	0.021	214	10190
Fiber glass (rigid)	0.033	304	9212
Urethane (rigid)	0.024	262	10917
Perlite	0.054	98	1815
Extruded polystyrene	0.029	182	6276
Urethane (roof deck)	0.021	221	10524

3. Research Methodology

3.1. Heat Transfer through a Wall Structure

Heat transfer through a building wall takes place in a three-step mechanism: conduction, convection, and radiation. The solar radiation on the outer surface of the wall is absorbed by the wall and transfered through the wall structure into the building indoor space through conduction. In this process, convective thermal transmission occurs as heat from the air outside the building wall is transferred to the outer surface of the wall and, then, from the inner surface of the wall to the air inside the building space.

The heat transfer process through a wall structure could be evaluated by the following equation:

$$Q = -\frac{kA\delta T}{\delta x} \qquad (1)$$

If outdoor-air and indoor-air temperatures are assumed to be T_o and T_i, as illustrated in Fig. 2., equation (1) can be rewritten as:

$$Q = \frac{kA(T_o - T_i)}{x} \qquad (2)$$

In terms of heat transfer per unit area, then:

$$\frac{Q}{A} = \frac{k(T_o - T_i)}{x} \qquad (3)$$

In a composite wall, Q passes through each layer of the wall. Therefore, for a composite wall Q can be written as:

$$\frac{Q}{A} = U(T_o - T_i) \qquad (4)$$

U as the overall heat transfer coefficient of the composite un-insulated wall can be calculated from the equation bellow:

$$U_{unins} = \frac{1}{R_{wall}} \qquad (5)$$

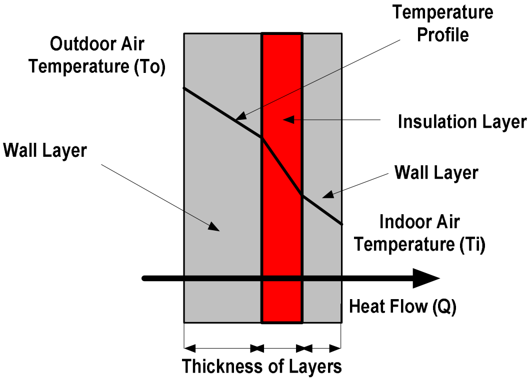

Fig. 2: Schematic drawing of heat flow and temperature profile through a wall layers

The total resistance of a composite un-insulated wall (R_{wall}) can be evaluated by the summation of the surface resistance of convective heat transfer of the inside and the outside surfaces and the internal layers' resistance as follows:

$$R_{wall} = \frac{1}{h_i} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \ldots + \frac{1}{h_o} \qquad (6)$$

Thermal resistance for an insulation layer can be added as $(x/k)_{ins}$ in the overall heat transfer coefficient and, thus, the overall heat transfer coefficient of an insulated wall can be written as:

$$U_{ins} = \frac{1}{R_{wall} + (\frac{x}{k})_{ins}} \qquad (7)$$

The difference between the overall heat transfer coefficient of insulated and un-insulated walls can be determined from the equation bellow:

$$\Delta U = U_{unins} - U_{ins} = \frac{1}{R_{wall}} - \frac{1}{R_{wall} + (x/k)_{ins}} \qquad (8)$$

AC systems are normally used during working hours in office buildings; that is, 40 hours a week. (Note: daily working hours are normally from 7:30

a.m. till 14:00 p.m.). Therefore, the annual cooling energy requirement (E) can be determined as the function of annual degree demand hours (ADH) of the AC systems and the heat transfer parameter (Q) as follows:

$$E = \frac{ADH \times Q}{COP} \quad (9)$$

Annual cooling energy requirement per unit area can be determined using the following equation:

$$\frac{E}{A} = \frac{ADH \times \Delta T}{(R_{wall} + (x/k)_{ins} \times COP} \quad (10)$$

3.2. Optimum Insulation Thickness

Heat transfer is proportional to the area and temperature difference. Furthermore, it is inversely proportional to the thickness. In another word, the greater the thickness is, the less heat transfer will be.

Insulation materials are employed in a wall structure to lower heat flow from outdoor air into indoor space. The insulation materials have a very low thermal conductivity. By the application of the insulation materials, the investment cost increases, while the cost of energy decreases, and, thus, at one point the thickness of material will be optimum, which contributes to the highest overall cost savings. Therefore, in order to have an economic AC system, a suitable insulation material with optimal thickness is required. This optimal condition can be achieved by conducting cost benefit analysis after the installation of insulation material. The optimum insulation thickness also depends on the cost of insulation material, electricity tariff, the lifetime of the building, inflation and discount rate, and AC system coefficient of performance [16].

The total cost of energy for cooling per unit area (C_t) can be evaluated by the equation bellow [3, 4]:

$$C_t = \frac{E}{A} \times C_E \quad (11)$$

By combining (10) and (11), we will have:

$$C_t = \frac{ADH \times \Delta T \times C_E}{(R_{wall+} (x/k)_{ins}) \times COP} \quad (12)$$

The present value of the total energy cost ($P(C_t)$) is equal to the present worth factor (PWF) times the total cost of energy per unit area as following [4, 10]:

$$P(C_t) = PWF \times C_t \quad (13)$$

The present worth factor (PWF) can be determined with the following equation [4, 10]:

$$PWF = \frac{1}{IR} \times \left[1 - \frac{1}{(1+IR)^N}\right] \quad (14)$$

In addition, to determine the cost benefit, the total cost of insulation (C_{ti}) should be specified per square meter, which can be calculated by the following equation:

$$C_{ti} = C_{ins} \times x_{ins} \quad (15)$$

In order to study the insulation materials from the economic point of view over the life cycle period, the present value (PV) of the system should be established. Therefore, the total PV, which is equal to the present value of energy cost plus the cost of insulation installation, can be evaluated by using the equation bellow:

$$PV = P(C_t) + C_{ti} \quad (16)$$

Through considering the above-mentioned equations, the total saved energy per unit area (TSE) can be expressed as:

$$TSE = \left(\frac{E}{A}\right)_{unins} - \left(\frac{E}{A}\right)_{ins}$$

(17)

The life cycle period cost saving (total saving, TS) is the net saving from the total cost of cooling without insulation (C_{tunins}) minus the sum of the total cost of energy for cooling with insulation (C_{tins}) and the total cost of insulation (C_{ti}). Thus, the equation becomes:

$$TS = C_{tunins} - (C_{tins} + C_{ti}) \quad (18)$$

4. Results and Discussions

In this section, the results of calculations for different insulation materials for Bandar Abbas and Bushehr are presented. To this end, annual operating hours for AC systems for Bandar Abbas and Bushehr were considered based on the cooling load required months.

Figs. 3 and 4 illustrate the effects of insulation thickness on the cost for Fiberglass- urethane and Urethane (roof deck) insulators in Bandar Abbas climate conditions, as the representative of the insulation materials studied. As it was shown in Figs. 3 and 4, by increasing the insulation thickness, the insulation cost increases; however, the energy cost decreases significantly up to a certain point where the insulation cost is almost equal to the energy cost. The total lifecycle cost-- as the summation of insulation cost and energy cost-- also depends on the insulation cost the value of which, at a certain thickness level, is minimum. Figs. 5 and 6 illustrate the effects of different insulation materials on the total cost for different insulation materials under Bandar Abbas and Bushehr climate conditions, respectively.

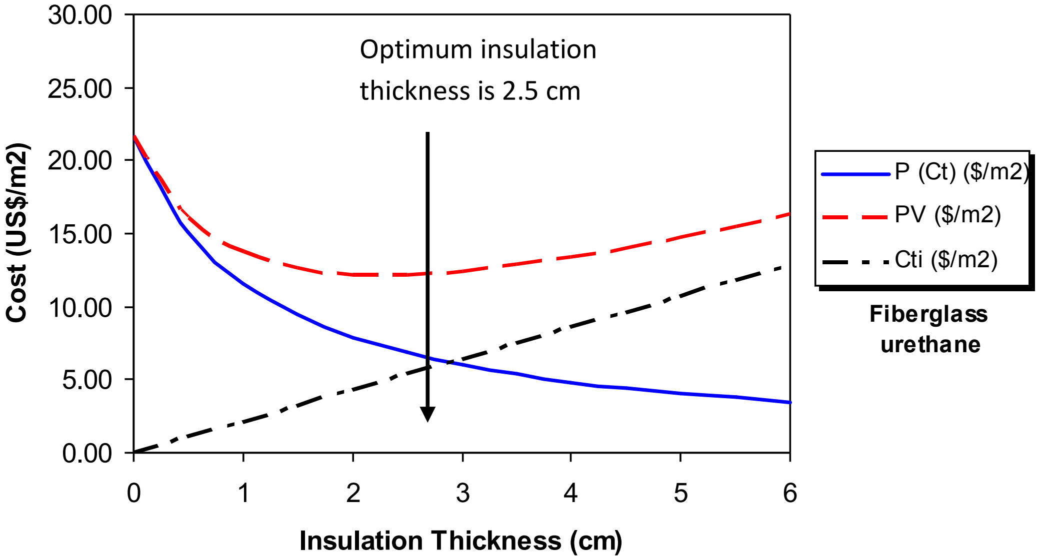

Fig. 3: Cost vs insulation thickness (Fiberglass-urethane)- Bandar Abbas

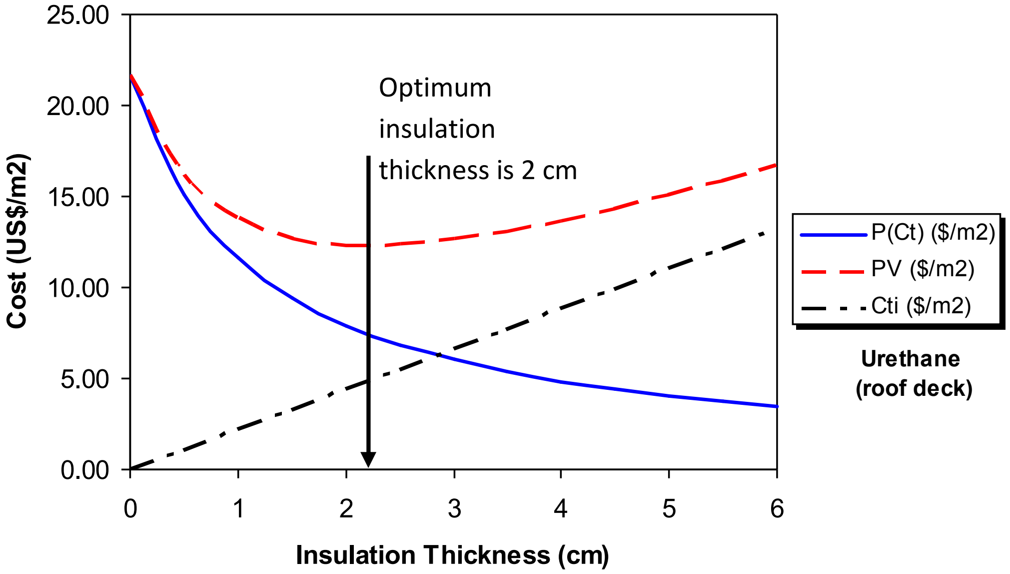

Fig. 4: Cost vs insulation thickness (Urethane, roof deck)- Bandar Abbas

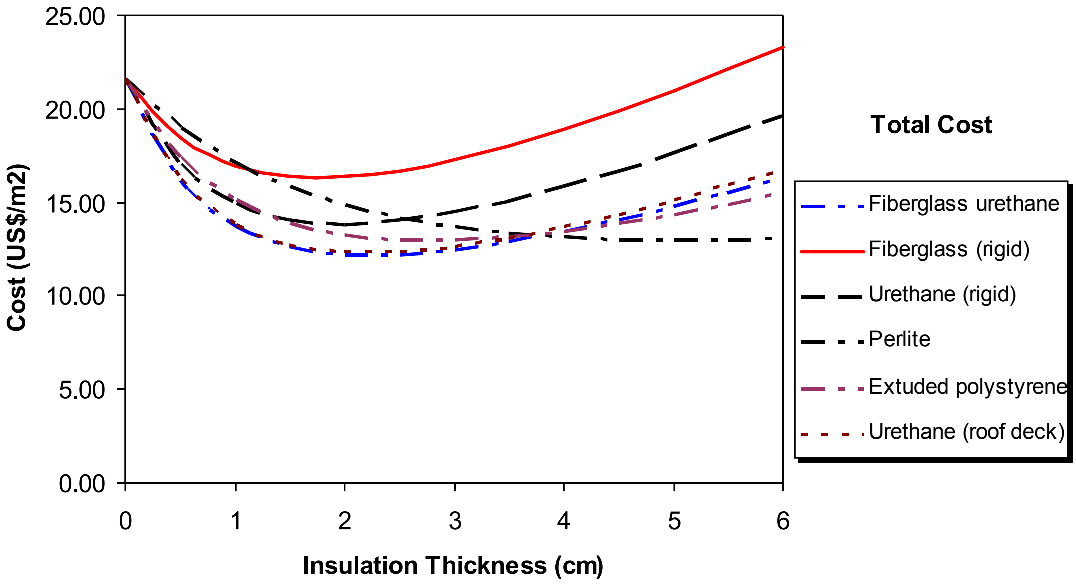

Fig. 5: Total cost vs insulation thickness- Bandar Abbas

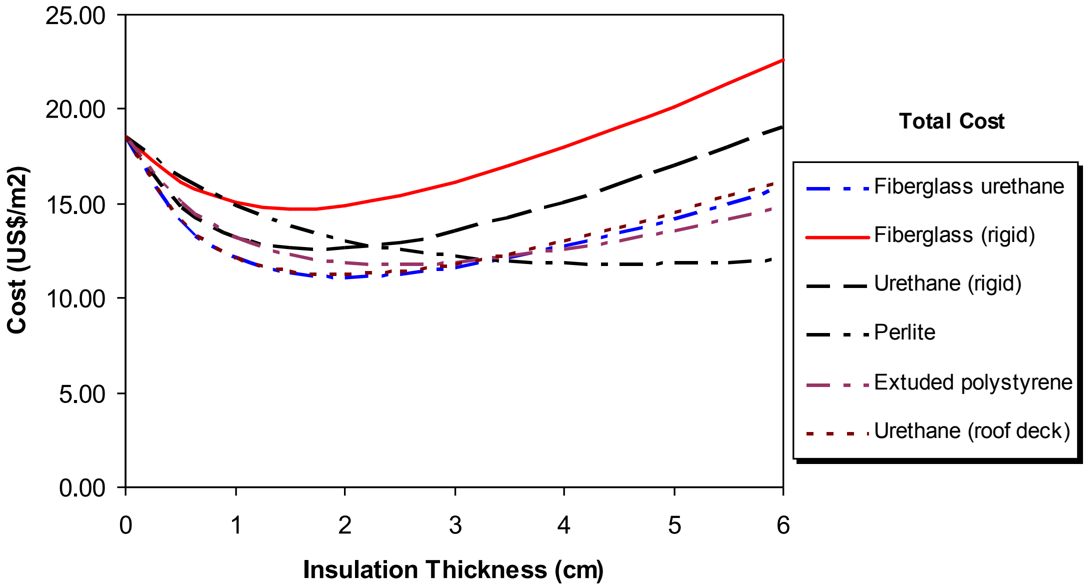

Fig. 6: Total cost vs. insulation thickness- Bushehr

The lifecycle cost saving depends also on the function of insulation thickness. Figs. 7 and 8 show the effects of insulation thickness on lifecycle period cost saving for different insulation materials in Bandar Abbas and Bushehr climate conditions, respectively. As it was shown in Figs. 7 and 8, the cost saving increases by increasing the insulation thickness, until it reaches a maximum amount beyond optimum thickness, at which the cost saving takes a reducing trend; such condition means additional thickness of insulation material is not economical anymore. Therefore, the optimum insulation thickness is achieved at the moment when the total saving starts to drop as the thickness of insulation material increases.

For instance, from Fig. 7, the optimum thickness is found to be 2.5 *cm* for Fibreglass–urethane and 2 *cm* for Urethane (roof deck) in Bandar Abbas climate condition (Note: the optimum thickness was clearly indicated for Fibreglass–urethane and

Urethane (roof deck) in Figs. 3 and 4 for Bandar Abbas). The optimum thicknesses for all the studied insulation materials are tabulated in Table 4 for more convenience.

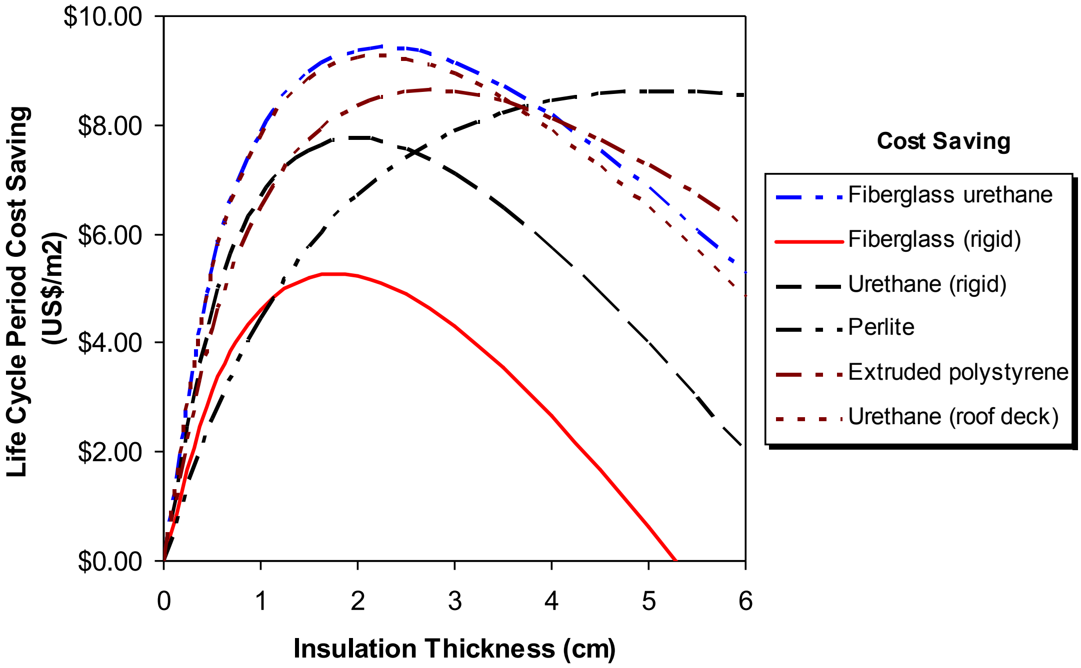

Fig. 7. Life cycle period cost saving vs. insulation thickness- Bandar Abbas

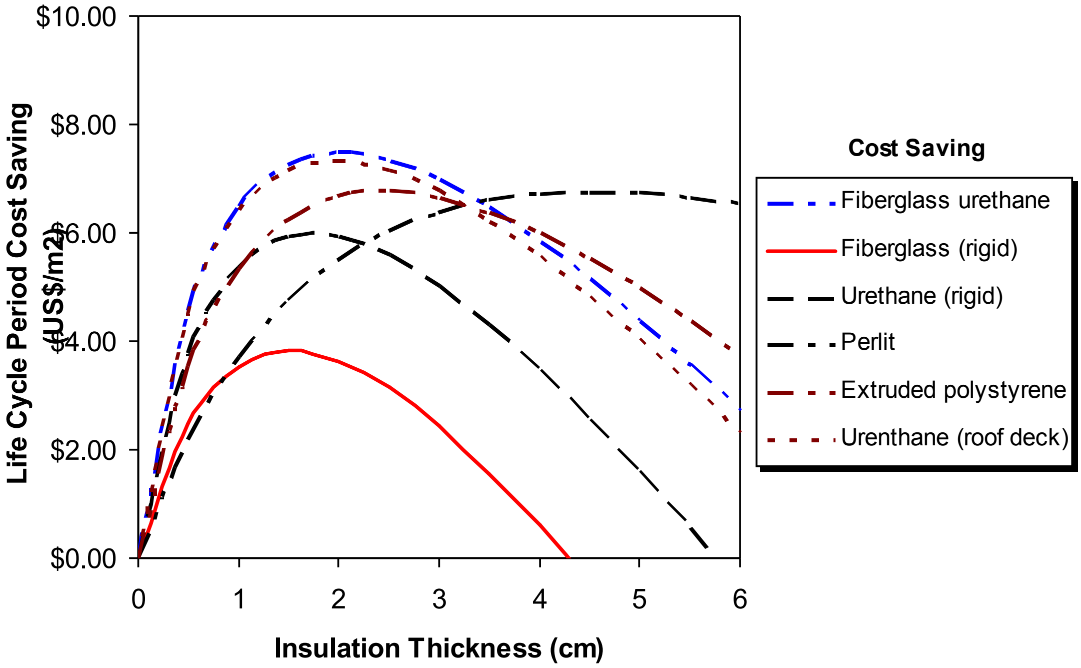

Fig. 8. Lifecycle period cost saving vs insulation thickness- Bushehr

Table 4: Optimum insulation thickness and cost saving for the insulation materials

Insulation material	Energy consumption ($kWh/year.m^2$)	Optimum thickness (cm)	Life cycle saving ($US\$/m^2$)
		Bandar Abbas	
Fiber glass-urethane	9.74	2.5	9.401
Fiber glass (rigid)	7.46	2	5.219
Urethane (rigid)	8.50	2	7.747
Perlite	8.93	5	8.626
Extruded polystyrene	9.3	3	8.616
Urethane (roof deck)	9.03	2	9.248
		Bushehr	
Fiber glass-urethane	8.38	2.5	7.339
Fiber glass (rigid)	5.54	1.5	3.827
Urethane (rigid)	6.51	1.5	5.932
Perlite	7.38	4.5	6.762
Extruded polystyrene	7.48	2.5	6.772
Urethane (roof deck)	7.77	2	7.337

As tabulated in Table 4, the study reveals that the Fiberglass –urethane insulator is the most cost effective material with the maximum cost saving of 9.401 US\$/m^2 followed by Urethane (roof deck) with 9.248 US\$/m^2 for Bandar Abbas. In addition, it has been found that Fiberglass –urethane and Urethane (roof deck) insulators also have the maximum cost saving for Bushehr with 7.339 US\$/m^2 and 7.337 US\$/m^2, respectively.

Considering the thermal conductivity of the insulation materials in Table 3, Perlite has the highest thermal conductivity among the insulation materials. The higher thermal conductivity of an insulation material means lower thermal resistance; therefore, the highest level of thickness is needed to be employed in order to reach the optimum thermal insulation which is 5 cm and 4.5 cm for Bandar Abbas and Bushehr cases, respectively. Moreover, the insulation material thickness is an important parameter in designing the process of a building since thick insulation material will reduce the space of the buildings considerably-- a fact which is not normally desired. Figs. 9 and 10 illustrate the annual energy savings for all the studied insulation materials. It has been found that Fiberglass-urethane has the highest level of annual energy saving potential. As a result, there is a relationship between the optimum thickness and thermal conductivity in the insulation materials.

In this section, a correlation between optimum thickness (x_{opt}) and thermal conductivity (k) is being derived and recommended for the insulation materials being employed in both Bandar Abbas and Bushehr. To this end, the optimum thickness of the considered insulation materials should be determined as the function of thermal conductivity. Figs. 11 and 12 show the optimum insulation thickness as the function of thermal conductivity for Bandar Abbas and Buhsehr, respectively. The study reveals that the correlations are non-linear and obey a polynomial function of $x_{opt} = a + bk + ck^2$. Where, $a = 4.0236$, $b = -148.67$, and $c = 3080$ for buildings located in Bandar abbas and $a = 5.8659$, $b = -271.46$, and $c = 4554.2$ for buildings located in Bushehr.

The above recommended correlations can be very applicable and useful since they enable the designers to easily estimate the optimum insulation thickness only by knowing thermal conductivity.

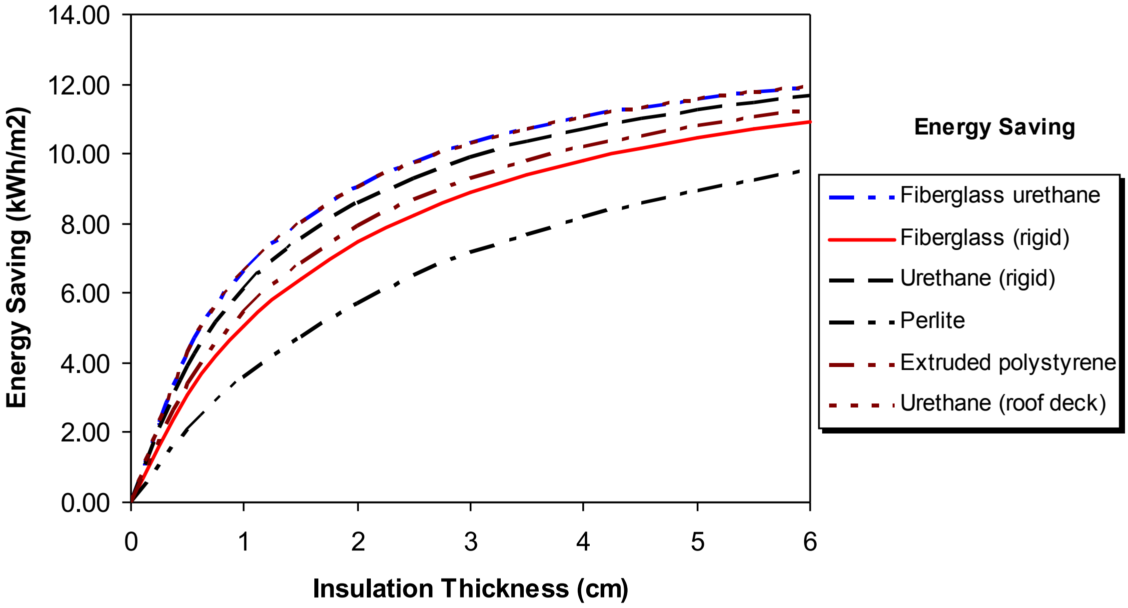

Fig. 9: Annual energy saving vs insulation thickness- Bandar Abbas

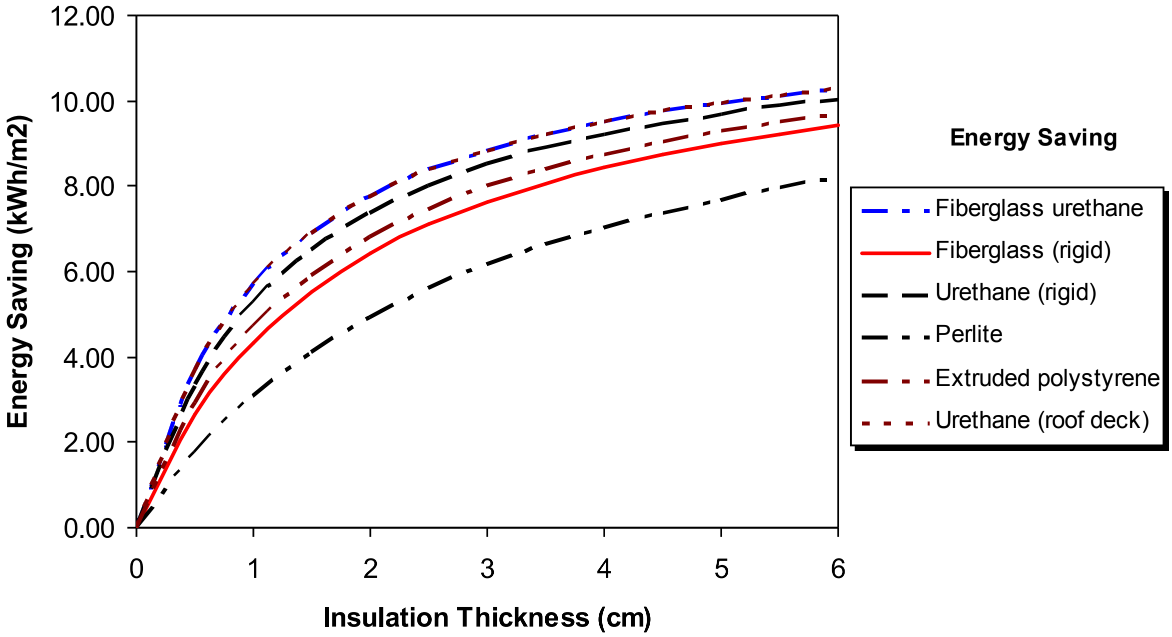

Fig. 10: Annual energy saving vs insulation thickness- Bushehr

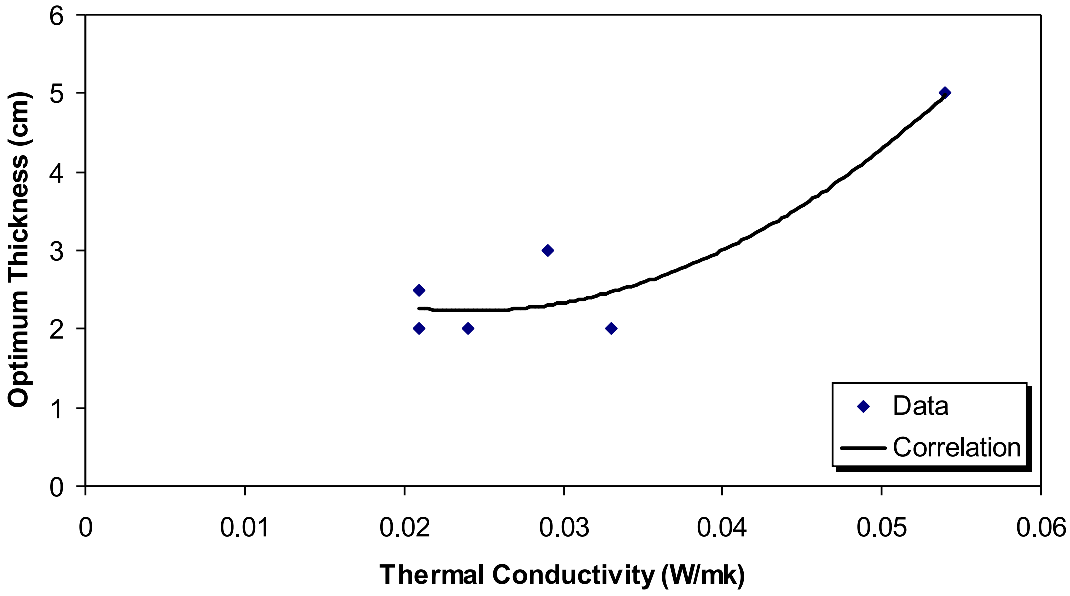

Fig. 11: Optimum insulation thickness as a function of thermal conductivity- Bandar Abbas

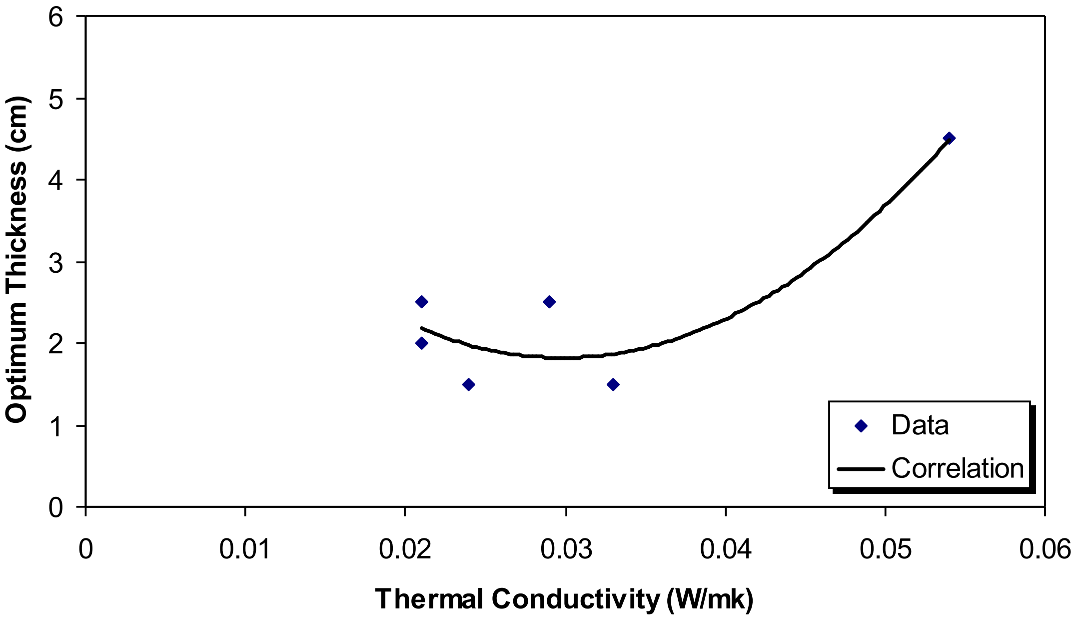

Fig. 12: Optimum insulation thickness as a function of thermal conductivity- Bushehr

5. Conclusions

In the present study, the optimum insulation thickness, based on the lifecycle period cost analysis, was determined for the building walls located in hot regions of Iran, namely Bandar Abbas and Bushehr. The study has showed that by increasing the thermal resistance of the insulation material, the insulation cost increases, while cooling cost decreases. In addition, the study has proved that the cost saving increases by increasing the insulation thickness, until it reaches a maximum amount and goes beyond a certain level. Then, the cost saving takes a reducing trend, which means the additional thickness of insulation material is not cost effective anymore. Therefore, the optimum insulation thickness is achieved when the total saving starts to drop as the thickness of insulation material increases.

The study has showed that the Fiberglass–urethane insulator is the most cost effective insulation material with the maximum cost saving of 9.401 $US\$/m^2$ followed by Urethane (roof deck) with 9.248 $US\$/m^2$ for Bandar abbas. Moreover, the study has showed that Fiberglass–urethane and Urethane (roof deck) insulators also have the maximum cost saving for Bushehr with 7.339 $US\$/m^2$ and 7.337 $US\$/m^2$, respectively.

In order to be able to find a cost effective insulation thickness for the available insulation materials, a correlation between the optimum thickness and thermal conductivity of the insulators is recommended for the considered hot regions. It has been found that the correlations are non-linear, which obeys a polynomial function of $x_{opt} = a + bk + ck^2$. Where, $a = 4.0236$, $b = -148.67$, and $c = 3080$ for buildings located in Bandar abbas and $a = 5.8659, b = -271.46$, and $c = 4554.2$ for buildings located in Bushehr.

Acknowledgment

The author would like to thank Chabahar Maritime University (CMU) in Iran for its financial supports to conduct the present research.

Nomenclature

A	Wall area (m^2)
C_{ins}	Insulation material cost ($US\$/m^3$)
C_E	Electricity price ($US\$/kWh$)
C_t	The total cost of energy per unit area ($US\$/m^2$)
C_{ti}	Total insulation cost ($US\$/m^2$)
E	Annual cooling energy requirements (kWh/m^2)
h	Convection heat transfer coefficients ($W/m^2{}^\circ C$)
IR	Inflation rate
k	Thermal conductivity ($W/m^\circ C$)
N	Life cycle period
$P(C_t)$	Present value of energy cost (US\$/m^2)
Q	Heat transfer (W)
R_{wall}	Wall resistance ($m^2{}^\circ C/W$)
T	Temperature ($^\circ C$)
U	Overall heat transfer coefficient ($W/m^2{}^\circ C$)
x	Thickness (m)

Subscripts

ins	Insulated
i	Inside (indoor)
o	Outside (outdoor)
opt	Optimum
tins	Total cost with insulation
tunins	Total cost without insulation (un-insulated)
unins	Un-insulated

Abbreviations

Air-Conditioning	AC
ADH	Annual degree demand hour
COP	Coefficient of performance
PWF	Present worth factor
PV	Present value
TS	Total saving
TSE	Total saved energy per unit area

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