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Effect of Insulation Thickness on Energy Consumption for Different Shaped Buildings

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Abstract. Control and management of energy consumption are becoming more and more important due to the rapid depletion of fossil energy resources and the increased environmental problems caused by them. A large amount of energy is consumed in the buildings. Therefore, priority is given to applications that reduce the amount of energy consumed during the utilization phase of buildings. Decisions regarding building shape and insulation thickness have a considerable effect on building energy costs. Therefore, this study will analyze the effect of insulation thickness on the energy consumption of residential buildings that have different shapes. The building shape is evaluated with an external envelope area to the building's gross volume (A/V) ratio and external wall area/floor area (EWA/FA) ratio. 4 building shapes with different external wall area are selected for this study. The maximum and minimum energy costs of each building shapes are calculated based on 14 different envelopes and 8 different orientation alternatives taking into consideration the solar gain. The effects of insulation thicknesses on energy costs for different shaped buildings are determined by comparing energy costs. It will provide pre-design information for future reference for residential buildings with less energy consumption and less environmental pollution.

Keywords: Energy cost, insulation thickness, building shape, energy consumption, building envelope.

1 Introduction

Today, with the rapid depletion of fossil energy sources and the increasing environmental problems caused by fossil fuels, supervision, and management of energy consumption becomes more important. The energy requirement of developing countries such as Turkey increases every year. According to the National Energy Conservation Center data, residential and service buildings consume 34% of total energy in Turkey [1]. Therefore, priority is given to applications that reduce the amount of energy consumed during the utilization phase throughout the life cycle of buildings. When reducing the cost of residential buildings, decreasing operational costs along with the construction costs will prove beneficial not only for the owner and/or user of the residence but also for the national economy. If we consider the big share of the residential sector within energy-related expenditures, it becomes obvious that ensuring a decrease in the housing energy expenses will also substantially contribute to decreasing energy-related expenditures of the country. Heating energy consumption in buildings have an important part of total energy consumption. 33% of energy-use in Turkey is for heating purposes [2]. A large amount of energy demand for residential buildings is caused by heat losses [3]. Thermal insulation application reduces environmental effects, carbon emissions and energy costs. Efficient heating applications can be provided by determining optimum insulation thickness.

There are a lot of studies on the insulation thickness of buildings. Kaynakli et al. [4] optimized the thermal insulation thickness used in the external walls of buildings composing of different applications. Gonzalo and Bovea [5] presented a methodology to analyze optimum insulation material for the building envelope. Reductions up to 40% in energy demand compared to regulations standards can be achieved in the telco-efficiency context. Kurekci [6] determined the optimum insulation thicknesses required in Turkey's 81 provincial centers based on four different fuels and five different insulation materials. Ozel et al. [7] investigated the optimum insulation thickness according to entransy loss for Bilecik in Turkey. The optimum thickness, which is determined by environmental impact analysis are 0.15 and 0.064 m for glass wool and rock wool respectively. The optimum insulation thicknesses depending on life cycle cost analysis are calculated as 0.012 and 0.07 m, respectively for glass wool and rock wool. Nyers et al. [8] analyzed the optimum thickness of the thermal insulation layer for the external wall and obtained the optimum thickness for energy-economic conditions in Serbia in 2014.

Besides the insulation thickness, plan shape affects the energy consumption of the buildings. Studies in literature are about the effect of insulation thickness or building shape, there is no study about the effect of insulation thickness and building shape together. Therefore, this study analyses the effect of insulation thickness on the energy consumption of residential buildings that have different shapes.

2 Methods

For analyzing the effect of insulation thickness on energy consumption of buildings that have different shapes, building envelope alternatives that have different insulation alternatives and different building shapes are identified. After that, the maximum and minimum annual energy costs (AEC) of residential buildings that have different shapes and insulation thicknesses are calculated based on 14 different envelope and 8 different orientation alternatives taking into consideration the solar gain. Calculated AEC is compared and the effects of insulation thicknesses on AEC for different shaped buildings are determined.

2.1 Identification of Building Insulation Alternatives

The building components forming a building envelope are the walls, roof and ground flooring. Different body and insulation materials used in the walls, roof and flooring, and different thicknesses will result in different energy costs of a building. External walls constitute the largest part of the building envelope and have a substantial impact on the energy costs of the building. Therefore, for the assessment of the insulation thickness on the energy costs of the buildings, extruded polystyrene foam (XPS) in different thicknesses (2 cm to 6 cm) are selected as wall insulation materials in this study. Since it is a more convenient system in buildings that are used for a prolonged period, such as housing, and there is a reduced risk of condensation as a result of steam diffusion, it is assumed that insulation is applied externally on the walls. It is assumed that brick and gasbeton can be used as wall body materials. A fixed wooden roof is approved. XPS with a thickness of 4 cm is deemed appropriate for use as an insulation material in ground flooring, and 10 cm thick glass wool is found appropriate for use in roofs. In building alternatives, double-glazed windows with wood casing are used as the transparent component type. Envelope alternatives of buildings are displayed in Table 1.

Table 1. Envelope alternatives

alternative	wall body material	roof insulation material	wall insulation material
t	19 cm brick	-	-
t10c	19 cm brick	10 cm glass wool	-
t2x10c	19 cm brick	10 cm glass wool	2 cm XPS
t3x10c	19 cm brick	10 cm glass wool	3 cm XPS
t4x10c	19 cm brick	10 cm glass wool	4 cm XPS
t5x10c	19 cm brick	10 cm glass wool	5 cm XPS
t6x10c	19 cm brick	10 cm glass wool	6 cm XPS
g	19 cm gasbeton	-	-
g10c	19 cm gasbeton	10 cm glass wool	-
g2x10c	19 cm gasbeton	10 cm glass wool	2 cm XPS
g3x10c	19 cm gasbeton	10 cm glass wool	3 cm XPS
g4x10c	19 cm gasbeton	10 cm glass wool	4 cm XPS
g5x10c	19 cm gasbeton	10 cm glass wool	5 cm XPS
g6x10c	19 cm gasbeton	10 cm glass wool	6 cm XPS

2.2 Identification of Building Shapes

In the studies that evaluated heating energy costs, building shapes were evaluated with A/V (external envelope area/building's gross volume) [9], [10], [11], [12], A/S (the area of building envelope per unit of heated area) [13], S/V (area of building envelope surface/volume of the building) [14] or EWA/FA (external wall area/floor area) ratios [15]. In this study, the building shape will be evaluated with A/V and EWA/FA ratio. Four building shapes with different external wall area are selected. They have the same characteristics and equal height, they are differentiated based on their plan shapes. It is assumed that alternatives to these shapes can be square, rectangular, H- or star-shaped. Buildings and residential units have approximately the same floor area and same characteristics. Windows and doors have approximately the same area. Only the external wall area of the buildings are varied.

2.3 Calculation of Annual Energy Costs (AEC)

In TS 825 [16], Turkey is divided into four climatic regions by provincial centers. Region 1 represents the areas that require the least energy for heating, and Region 4 represents the areas that require the most energy for heating. The heating energy demand and annual fuel amounts for project alternatives are calculated for the second climate zone, which is a temperate climate zone and which also covers Istanbul. Wall alternatives are checked for the presence of condensation and no condensation is found in these wall alternatives. To calculate heating energy costs, the "TS 825 Heat Requirement Calculations" computer program is used. This calculation program, designed by Izoder, is based on the "TS 825 Heat Insulation Rules in Buildings" standard and Turkey's meteorological data for the last 20 years. Using this program, it is possible to calculate condensation values and the specific heat loss as defined in the "TS 825 Thermal Insulation Requirements for Buildings" standard,and compare the calculated values to the thresholds defined in the standard and hence evaluate the conformity of the designed building to national legislation on energy efficiency. The program operation is parallel to the TS 825 standard. First, data regarding the building subject to the standard are entered into the program, and then the building's annual heating energy demand and condensation values are calculated and checked against the criteria outlined in the standard. In the defined calculation method, annual heating energy demand is calculated by adding the monthly heating energy demand for the heating period. Hence, it becomes possible to make a more realistic evaluation of the thermal performance of the building. Also, the program enables the designer to evaluate the proposed design's capacity to take advantage of solar energy [17].

It is assumed that natural gas is consumed in all project alternatives. Calculation of heating energy costs is based on the natural gas prices applicable for March 2019 in Istanbul [18]. AECs are calculated both based on different wall alternatives and also different orientations. Taking into consideration the solar gain of the buildings, AECs are calculated based on each shape and envelope alternative with eight different orientations. AECs that are calculated in TL is changed to $. The exchange rate of $ is taken from the Central Bank of the Republic of Turkey for 1 March 2019 [19].

3 Results and Discussion

AECs per m^2 of buildings with 4 different building shapes (have different EWA/FA ratio and A/V ratio) are calculated based on 14 different envelopes and 8 different orientation alternatives. In Table 2, Figure 1 and Figure 2, buildings with different building shapes (EWA/FA and A/V ratio) and insulation alternatives are compared in terms of minimum AECs per m^2 considering 8 different orientation alternatives. AEC decreases with the usage of insulation material. When insulation material thickness increases, AEC decreases. AEC per m^2 of square building without insulation material

(EWA/FA=2.700 and A/V=0.348) is %179.55 more than the same building with 6 cm XPS wall insulation and 10 cm glass wool roof insulation. AEC per m^2 of rectangular building without insulation material (EWA/FA=2.811 and A/V=0.356) is %182.35 more than the same building with 6 cm XPS wall insulation and 10 cm glass wool roof insulation. AEC per m^2 of star-shaped building without insulation material (EWA/FA=3.139 and A/V=0.381) is %192.89 more than the same building with 6 cm XPS wall insulation and 10 cm glass wool roof insulation. AEC per m^2 of H-shaped building without insulation material (EWA/FA=3.606 and A/V=0.415) is %203.54 more than the same building with 6 cm XPS wall insulation and 10 cm glass wool roof insulation. As it is seen in Table 2, Figure 1 and Figure 2, when insulation material thickness increases, AEC decreases. AEC per m^2 of different shaped buildings increases rapidly when the roof or wall insulation applied to a building without insulation. AEC per m^2 of buildings decreases slowly in the buildings with wall insulation 2 cm to 6 cm buildings with different building shapes (EWA/FA and A/V ratio). Insulation alternatives are compared in terms of maximum AECs per m^2 considering 8 different orientation alternatives in Table 3.. The changes of minimum AECs per m^2 according to insulation thicknesses are close to the changes of maximum AECs per m^2. As it is seen in Table 1 and 2; when EWA/FA or A/V ratio increases, both minimum, and maximum AEC increases even though the usage of insulation and increasing thickness of insulation.

Table 2. Assessment of minimum AEC per m^2 of buildings that have different shapes with different insulation thicknesses.

EWA/ FA	2.700		2.811		3.139		3.606	
A/V	0.348		0.356		0.381		0.415	
	AEC per m^2 ($/$m^2$)	relative AEC per m^2	AEC per m^2 ($/$m^2$)	relative AEC per m^2	AEC per m^2 ($/$m^2$)	relative AEC per m^2	AEC per m^2 ($/$m^2$)	relative AEC per m^2
wall body material- 19 cm brick								
t	19.71	279.55	20.75	282.35	22.29	292.89	23.72	303.54
t10c	14.33	203.20	15.21	206.98	16.66	218.95	18.15	232.22
t2x10c	8.57	121.48	8.99	122.34	9.51	124.94	10.02	128.16
t3x10c	7.96	112.83	8.32	113.25	8.74	114.85	9.13	116.83
t4x10c	7.53	106.83	7.88	107.25	8.24	108.21	8.55	109.39
t5x10c	7.26	102.92	7.57	102.99	7.87	103.38	8.13	103.97
t6x10c	7.05	100.00	7.35	100.00	7.61	100.00	7.82	100.00
wall body material- 19 cm gasbeton								
g	18.02	262.19	18.94	264.23	20.13	272.04	21.16	279.52
g10c	12.65	184.08	13.42	187.22	14.54	196.47	15.64	206.57
g2x10c	8.07	117.45	8.45	117.92	8.86	119.76	9.25	122.15
g3x10c	7.58	110.33	7.92	110.53	8.27	111.73	8.59	113.47
g4x10c	7.27	105.87	7.59	105.89	7.88	106.51	8.13	107.38
g5x10c	7.05	102.63	7.35	102.58	7.61	102.80	7.80	103.06
g6x10c	6.87	100.00	7.17	100.00	7.40	100.00	7.57	100.00

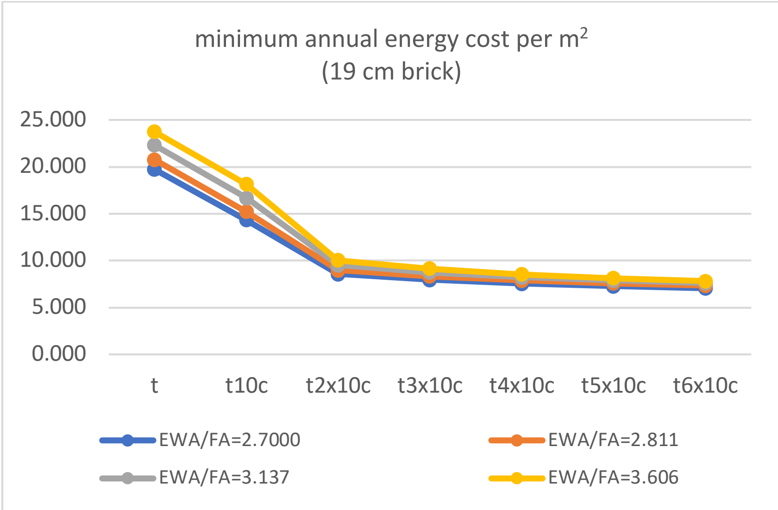

Fig. 1. Minimum annual energy cost per m^2 of buildings that have different shapes with different insulation thickness (wall body material-19 cm brick).

Table 3. Assessment of maximum AEC per m^2 of buildings that have different shapes with different insulation thickness.

EWA/ FA	2.700		2.811		3.139		3.606	
A/V	0.348		0.356		0.381		0.415	
	AEC per m^2 ($/m^2)	relative AEC per m^2	AEC per m^2 ($/m^2)	relative AEC per m^2	AEC per m^2 ($/m^2)	relative AEC per m^2	AEC per m^2 ($/m^2)	relative AEC per m^2
wall body material- 19 cm brick								
t	19.75	279.54	20.80	281.56	22.32	292.71	23.78	301.69
t10c	14.35	203.13	15.21	206.35	16.67	218.60	18.22	231.10
t2x10c	8.60	121.67	8.99	122.33	9.54	125.15	10.08	127.82
t3x10c	7.98	112.96	8.32	113.17	8.76	114.92	9.19	116.58
t4x10c	7.56	107.05	7.88	107.23	8.27	108.42	8.59	109.02
t5x10c	7.28	103.09	7.57	103.10	7.90	103.59	8.19	103.93
t6x10c	7.07	100.00	7.35	100.00	7.63	100.00	7.88	100.00
wall body material- 19 cm gasbeton								
g	18.04	261.28	18.99	263.69	20.14	271.63	21.22	278.40
g10c	12.67	183.48	13.46	186.90	14.56	196.35	15.71	206.07
g2x10c	8.08	116.99	8.49	117.89	8.89	119.95	9.30	121.99
g3x10c	7.61	110.14	7.98	110.76	8.32	112.18	8.63	113.19
g4x10c	7.30	105.71	7.64	106.04	7.91	106.73	8.20	107.54
g5x10c	7.06	102.22	7.39	102.62	7.62	102.79	7.87	103.25
g6x10c	6.91	100.00	7.20	100.00	7.42	100.00	7.62	100.00

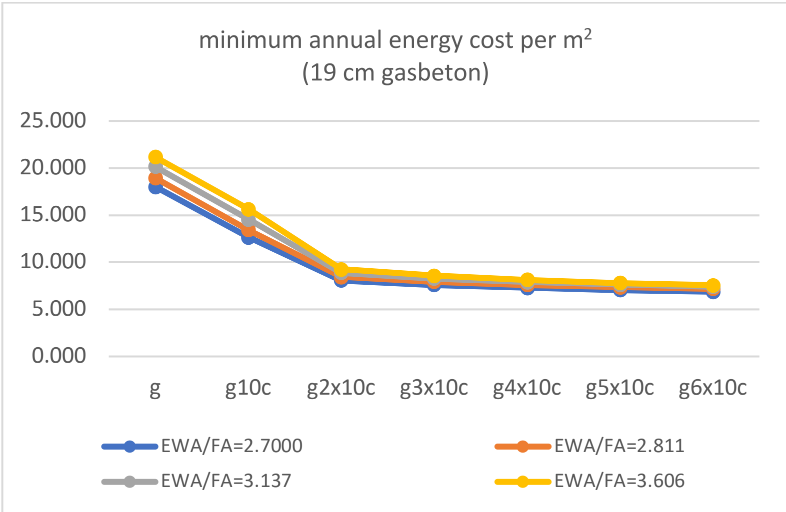

Fig. 2. Minimum annual energy cost per m^2 of buildings that have different shapes with different insulation thickness (wall body material-19 cm gasbeton).

4 Conclusions

In line with the amount of energy consumed by subsystems that provide comfort; the drop-off in the energy resources used, dependency to other countries for these resources, harms of gases emitted by the consumption of energy, increasing air pollution and related global warming issues have gained serious importance. In Turkey, heat loses from the buildings is one of the primary sources of energy waste. Based on all the preceding, it is required to produce and operate residential buildings that provide the necessary thermal comfort conditions while consuming minimum energy. And one way of ensuring this is the building envelope design.

The effect of insulation thickness on the energy consumption of residential buildings that have different shapes is analyzed in this study. When insulation material thickness increases, AEC decreases. AEC per m^2 of different shaped buildings increases rapidly when the roof or wall insulation applied to a building without insulation. AEC per m^2 of buildings decreases slowly in the buildings with wall insulation 2 cm to 6 cm buildings with different building shapes (EWA/FA and A/V ratio). It was seen that increasing the thickness is not necessary to achieve more effective insulation. As the thickness of the insulation material increases, the saving achieved in annual heating costs increases less compared to the increase in insulation material thickness. Looking at the wall body material usages, gasbeton provides the most effective saving in heating energy compared to other materials.

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