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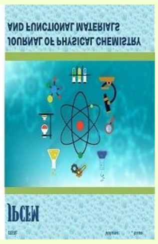

CO_2 Emission and Cost Analysis for Different Building Elements and Insulation Materials Based on Optimum Insulation Thickness

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ABSTRACT

In this study it is aimed that to analyze the relation between CO2 emissions of fuel over insulation materials and insulation thickness. For this purpose optimum insulation thickness for different building structural elements such as ground floor, external insulated wall and flat roof have been determined for four insulation materials (as rockwool, glasswool, extruded polystrene and expanded polystren) and their CO2 emissions have also been presented in comparison with fuel consumption, annual cost and total cost savings. Calculations were made for five chosen (Antalya, İstanbul, Ankara, Sivas, Erzurum) cities that represent the different climatic regions of Turkey and natural gas was chosen as fuel. Degree-Day Method has been used for optimum insulation calculations including heating and cooling periods while present worth factor has been calculated over 10 years. Lowest CO_2 emission results were obtained with rockwool considering external walls for the insulation thicknesses calculated due to both of heating+cooling loads while worst results were obtained for XPS. Glasswool and EPS also followed rockwool with their lower CO_2 emission values. Erzurum presented the highest CO2 emission values caused by it's amount of fuel consumption while CO_2 emission values decreased with increasing insulation thickness for provinces.

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1. Introduction

Studies on the increase in energy consumption and the careful consumption of energy sources have shown that energy saving has become a necessity for efficient use of energy resources in recent years. Insulation applications in buildings that use the majority of energy in cities can be a simple and effective solution to this problem. However, it has been observed that the applications made more than a certain thickness increase the insulation cost and maximize the total cost [1].Therefore, the calculation of optimum insulation thickness that can be applied to buildings has gained importance in order to minimize both of energy demand and total cost. Most of the studies on this subject are based on the determination of insulation thicknesses for different climate zones [2-3], different insulation materials [4-6] and different wall types [7]. Beside it, environmental effect of insulation materials in relation with fuels used for heating has generally been neglected. There are a few studies that focused on this topic considering different climatic regions and insulation materials [8-10]. Most of these studies combined exergy or entransy which is defined as heat transfer capacity analysis with thermoeconomic methodology and focused on reducing the environmental

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impact of combustion parameters, as well as maximizing cost savings [10-16].

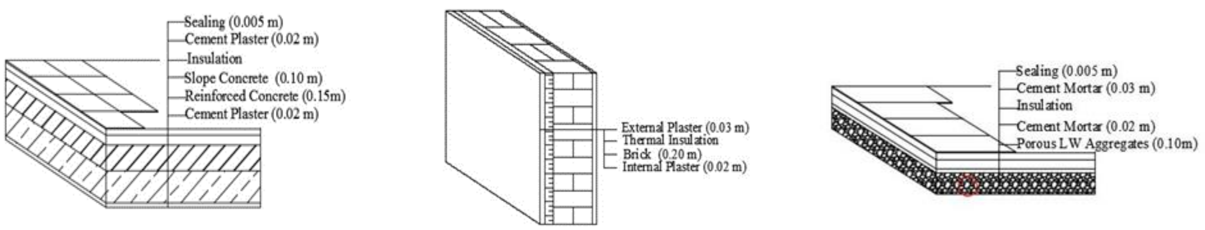
In this study it is aimed that to analyze the relation between CO_2 emissions of fuel over insulation materials and insulation thickness. For this purpose optimum insulation thickness for different building structural elements such as ground floor, external insulated wall and flat roof have been determined for four insulation materials (as rockwool, glasswool, extruded polystrene and expanded polystren) and their CO_2 emissions have also been presented in comparison with fuel consumption, annual and total cost savings. Calculations were made for five chosen cities (Antalya, İstanbul, Ankara, Sivas, Erzurum) that represent the different climatic regions of Turkey and natural gas as fuel. Degree-Day Method has been used for optimum insulation calculations including heating and cooling periods while present worth factor has been calculated over 10 years. CO_2 emission values of fuel for different insulation materials have also been assessed in order to analyze the environmental effect of their combinations with building structural elements.

2. Method

Structural elements have been matched with four insulation materials. Calculations were made for different combinations. Table 1 presents the code names of mentioned combinations while Figure 1 presents the structural layers of flat roof, external insulated wall and ground floor respectively. Table 3 shows the heating and cooling degree days of selected cities.

Table 1. Code names of mentioned combinations

Code	**GF-RW**	**GF-GW**	**GF-XPS**	**GF-EPS**
Definition	Ground Floor-Rockwool	Ground Floor-Glasswool	Ground Floor-ExtrudedPolystrene	Ground Floor-Expanded Polystrene
Code	**EW-RW**	**EW-GW**	**EW-XPS**	**EW-EPS**
Definition	External Wall -Rockwool	External Wall-Glasswool	External Wall-Extruded Polystrene	External Wall- Expanded Polystrene
Code	**R-RW**	**R-GW**	**R-XPS**	**R-EPS**
Definition	Roof -Rockwool	Roof- Glasswool	Roof -Extruded Polystrene	Roof-Expanded Polystrene



Roof External Insulated Wall Ground Floor

Figure 1. Layers of flat roof, external insulated wall and ground floor [15].

Table 2. Climatic properties of chosen cities [1]

Cities	Climatic Region	Heating-Degree Days (HDD)	Cooling-DegreeDays (CDD)
Antalya	I.	1083	562
İstanbul	II.	1865	159
Ankara	III.	2677	109
Sivas	IV.	3444	27
Erzurum	V.	4827	7

2.1. Annual Cooling and Heating Loads

In this study, optimum insulation thickness values were calculated by assuming that heat loss occurs only from the outer walls, roofs and ground floors.

Heat loss (W) on the unit surface of the structural elements calculated as

$$q = U.\Delta t \quad (1)$$

where U is the heat transfer coefficient [5]. The annual energy cost ($\$/m^2$) required to heat the unit area is calculated as:

$$E_{A,H} = \frac{C_f.U}{H_u.\eta} HDD \quad (2)$$

here C_f is the fuel cost ($\$ / m^3$) and H_u is the system efficiency of fuel (J / m^3). Fuel consumption per year is given in

$$M_F = \frac{86{,}400HDD}{(R_{ST}+(x/k))\eta H_u}\ (kg/year) \quad (3)$$

where R_{ST} (W/mK) is heat transmission resistance of layers of structural element without insulation, x (m) is insulation thickness and k (W/mK) is heat transmission coefficient.

The cost of energy required for cooling can be calculated by Eq. 4:

$$E_{A,C} = \frac{C_{elt}\,U}{COP} CDD \quad (4)$$

C_{elt} represents the unit price of electricity ($ / kWh) and COP is the performance coefficient of the cooling system and accepted as 2.5 for this study [14]. Table 3 presents the parameters and their values used in the calculations.

Table 3. Parameters used in the calculations [1,15].

Fuel (heating)	Natural Gas	Insulation	k (W/mK)	Unit price ($)
H_u	34.542x10^6 (J/kg)	Rockwool	0.040	80
η	0.93	Glasswool	0.032	103
Unit Price	0.306 ($)	Extruded Polystrene	0.031	224
Energy (Cooling)	Electricity	Expanded Polystrene	0.039	120
Unit Price	0.106 ($/KWh)			
COP	2.5	R_{ST} (GF-EW-R)	0.520 -0.670 -0.388 (W/m^2K)	

2.2. Calculation of Combustion Process

Increasing insulation thickness in buildings causes a decreasing with heat loss. Decreasing on fuel consumption and air pollution is also subjected. The general chemical burning formula of natural gas can be defined as [14]

$$C_gH_yO_zN_t + \propto A(Q_2 + 3{,}76N_2) \rightarrow gCO_2 + \frac{y}{2}H_2O + (\propto -1)AO_2 + BN_2 \quad (5)$$

The constants A and B can be calculated by the equations given below

$$A = \left(g + \frac{y}{4} + w - \frac{z}{2}\right) \quad (6)$$

$$B = 3{,}76 \propto \left(g + \frac{y}{4} + w + \frac{z}{2}\right) + \frac{t}{2} \quad (7)$$

In (5), NOx and CO emissions are neglected. The emission rate of combustion products resulting from the burning 1 kg of fuel can be calculated by

$$M_{CO_2} = \frac{gCO_2}{M} = kgCO_2/kg\ fuel \quad (8)$$

The total emission of CO_2 could be calculated if the right hand side the above expressions by M_F, which is total burned fuel within HDD. The equations of emission are given in

$$M_{CO_2} = \frac{44g}{M} M_F \quad (9)$$

where M is the weight of mol for fuel which can be calculated using

$$M = 12g + y + 16z + 2w + 14t\ kg/kmol \quad (10)$$

2.3. Calculation of Optimum Insulation Thickness

Insulation cost (C_{INS}) could be calculated as

$$C_{INS} = C_{mtrl}x \quad (11)$$

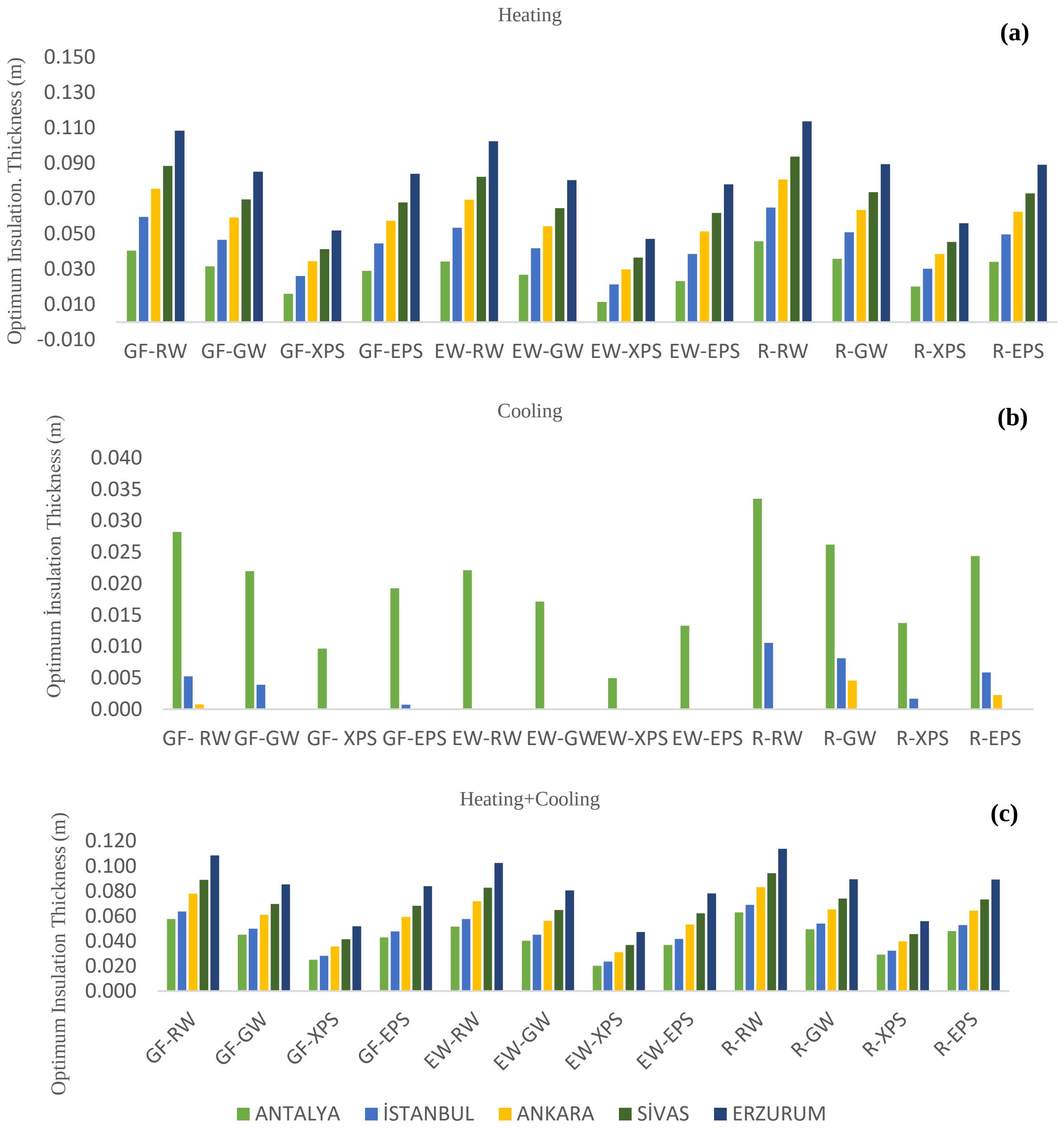


Figure 2. Optimum insulation thicknesses for **a)** Heating load **b)** Cooling Load **c)** Heating and Cooling Loads

where C_{mtrl} (\$/m^3) presents the unit price of insulation material while x (m) is the thickness of insulation. The net energy saving for heating compared to a certain period of time is calculated by Eq. 12:

$$S_{year} = \frac{PWF\ C_f U}{H_u\ \eta} HDD - C_{mtrl} x \qquad (12)$$

Present Worth Factor (PWF) is used for the calculation of fuel cost over a lifetime. It depends on inflation and interest rates. The calculation method is presented in Reference [4-5] and calculated as 8.4 for this study. Optimum insulation thickness (m) for heating is calculated as

$$x_{opt,H} = 293.94 \left(\frac{PWFC_{fuel}kHDD}{C_{mtrl}H_u\eta}\right)^{1/2} - R_{ST} \qquad (13)$$

The annual energy cost (\$/m^2) saving and optimum insulation thickness (m) required to cool the unit area can be calculated using equations (14) and (15), respectively

$$S_{year} = \frac{PWF\ C_{elkt}\ U}{COP} CDD - C_{mtrl} x \qquad (14)$$

$$x_{opt,C} = 293.94 \left(\frac{PWFC_{elkt}kCDD}{C_{mtrl}COP}\right)^{1/2} - R_{ST}k \qquad (15)$$

Optimum insulation thickness for both of heating and cooling loads could be calculated by Eq. 16.

$$x_{opt,H,C} = 293.94 \left[\left(\frac{PWFC_f kHDD}{C_{mtrl}LHV\eta_s}\right) + \left(\frac{PWFC_{elkt}kCDD}{C_{mtrl}COP}\right)\right]^{1/2} - R_{ST}k \qquad (16)$$

Table 4. Annual and total cost savings ($\$/m^2$) in relation with fuel consumption and CO_2 emissions (kg/m^2year) for Ground Floor

	Heating				**Heating+Cooling**			
GF-RW	$S_{A,H}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$	$S_{A,H,C}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$
ANTALYA	1.132	6.280	1.904	5.041	1.260	5.978	1.487	3.935
İSTANBUL	2.189	13.627	2.499	6.616	2.226	13.611	2.377	6.293
ANKARA	3.324	21.885	2.994	7.926	3.346	21.880	2.922	7.734
SİVAS	4.416	30.023	3.396	8.990	4.421	30.023	3.380	8.947
ERZURUM	6.415	45.213	4.021	10.643	6.416	45.213	4.017	10.634
GF-GW	$S_{A,H}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$	$S_{A,H,C}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$
ANTALYA	1.124	6.184	1.933	5.117	1.254	5.878	1.509	3.994
İSTANBUL	2.178	13.485	2.536	6.714	2.216	13.469	2.412	6.386
ANKARA	3.310	21.706	3.039	8.044	3.333	21.701	2.965	7.849
SİVAS	4.400	29.813	3.447	9.124	4.405	29.813	3.430	9.080
ERZURUM	6.397	44.955	4.080	10.802	6.398	44.955	4.077	10.792
GF-XPS	$S_{A,H}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$	$S_{A,H,C}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$
ANTALYA	0.857	3.594	2.805	7.427	1.045	3.149	2.190	5.797
İSTANBUL	1.827	9.494	3.681	9.746	1.882	9.470	3.502	9.270
ANKARA	2.890	16.548	4.411	11.676	2.923	16.541	4.304	11.393
SİVAS	3.924	23.708	5.003	13.243	3.931	23.707	4.979	13.180
ERZURUM	5.833	37.378	5.923	15.679	5.834	37.378	5.917	15.665
GF-EPS	$S_{A,H}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$	$S_{A,H,C}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$
ANTALYA	1.010	5.000	2.303	6.097	1.165	4.635	1.798	4.759
İSTANBUL	2.029	11.706	3.022	8.001	2.074	11.686	2.875	7.610
ANKARA	3.132	19.431	3.621	9.585	3.159	19.426	3.533	9.353
SİVAS	4.198	27.137	4.107	10.872	4.204	27.137	4.087	10.820
ERZURUM	6.157	41.654	4.862	12.871	6.159	41.654	4.858	12.860

Table 5. Annual and total cost savings ($\$/m^2$) in relation with fuel consumption and CO_2 emissions (kg/m^2year) for External Wall

	Heating				**Heating+Cooling**			
EW-RW	$S_{A,H}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$	$S_{A,H,C}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$
ANTALYA	0.744	3.507	1.904	5.041	0.872	3.205	1.487	3.935
İSTANBUL	1.521	8.500	2.499	6.616	1.558	8.484	2.377	6.293
ANKARA	2.365	14.315	2.994	7.926	2.387	14.310	2.922	7.734
SİVAS	3.182	20.145	3.396	8.990	3.187	20.144	3.380	8.947
ERZURUM	4.686	31.172	4.021	10.643	4.687	31.172	4.017	10.634
EW-GW	$S_{A,H}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$	$S_{A,H,C}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$
ANTALYA	0.736	3.426	1.933	5.117	0.866	3.120	1.509	3.994
İSTANBUL	1.510	8.374	2.536	6.714	1.547	8.357	2.412	6.386
ANKARA	2.351	14.150	3.039	8.044	2.374	14.145	2.965	7.849
SİVAS	3.166	19.949	3.447	9.124	3.171	19.949	3.430	9.080
ERZURUM	4.667	30.929	4.080	10.802	4.668	30.929	4.077	10.792
EW-XPS	$S_{A,H}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$	$S_{A,H,C}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$
ANTALYA	0.469	1.390	2.805	7.427	0.657	0.945	2.190	5.797
İSTANBUL	1.159	4.936	3.681	9.746	1.214	4.913	3.502	9.270
ANKARA	1.931	9.547	4.411	11.676	1.964	9.540	4.304	11.393
SİVAS	2.690	14.398	5.003	13.243	2.697	14.398	4.979	13.180
ERZURUM	4.103	23.907	5.923	15.679	4.105	23.907	5.917	15.665
EW-EPS	$S_{A,H}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$	$S_{A,H,C}$	S_T	$\boldsymbol{M_F}$	$\boldsymbol{M_{CO2}}$
ANTALYA	0.622	2.452	2.303	6.097	0.777	2.087	1.798	4.759
İSTANBUL	1.361	6.805	3.022	8.001	1.406	6.785	2.875	7.610
ANKARA	2.173	12.086	3.621	9.585	2.200	12.081	3.533	9.353
SİVAS	2.964	17.483	4.107	10.872	2.970	17.483	4.087	10.820
ERZURUM	4.428	27.839	4.862	12.871	4.429	27.839	4.858	12.860

Table 6. Annual and total cost savings ($/m^2) in relation with fuel consumption and CO_2 emissions (kg/m^{2}year) for Roof.

	Heating				Heating+Cooling			
R-RW	$S_{A,H}$	S_T	M_F	M_{CO2}	$S_{A,H,C}$	S_T	M_F	M_{CO2}
ANTALYA	1.716	10.760	1.904	5.041	1.844	10.458	1.487	3.935
İSTANBUL	3.194	21.646	2.499	6.616	3.231	21.630	2.377	6.293
ANKARA	4.766	33.580	2.994	7.926	4.789	33.575	2.922	7.734
SİVAS	6.272	45.190	3.396	8.990	6.277	45.190	3.380	8.947
ERZURUM	9.016	66.640	4.021	10.643	9.017	66.640	4.017	10.634
R-GW	$S_{A,H}$	S_T	M_F	M_{CO2}	$S_{A,H,C}$	S_T	M_F	M_{CO2}
ANTALYA	1.707	10.651	1.933	5.117	1.837	10.345	1.509	3.994
İSTANBUL	3.183	21.492	2.536	6.714	3.221	21.476	2.412	6.386
ANKARA	4.753	33.388	3.039	8.044	4.775	33.383	2.965	7.849
SİVAS	6.256	44.967	3.447	9.124	6.261	44.967	3.430	9.080
ERZURUM	8.998	66.370	4.080	10.802	8.999	66.370	4.077	10.792
R-XPS	$S_{A,H}$	S_T	M_F	M_{CO2}	$S_{A,H,C}$	S_T	M_F	M_{CO2}
ANTALYA	1.440	7.580	2.805	7.427	1.629	7.135	2.190	5.797
İSTANBUL	2.832	17.019	3.681	9.746	2.887	16.995	3.502	9.270
ANKARA	4.333	27.748	4.411	11.676	4.365	27.742	4.304	11.393
SİVAS	5.780	38.381	5.003	13.243	5.787	38.380	4.979	13.180
ERZURUM	8.434	58.311	5.923	15.679	8.436	58.311	5.917	15.665
R-EPS	$S_{A,H}$	S_T	M_F	M_{CO2}	$S_{A,H,C}$	S_T	M_F	M_{CO2}
ANTALYA	1.594	9.284	2.303	6.097	1.749	8.919	1.798	4.759
İSTANBUL	3.034	19.530	3.022	8.001	3.079	19.511	2.875	7.610
ANKARA	4.574	30.931	3.621	9.585	4.601	30.926	3.533	9.353
SİVAS	6.054	42.108	4.107	10.872	6.060	42.108	4.087	10.820
ERZURUM	8.759	62.886	4.862	12.871	8.760	62.886	4.858	12.860

3. Results and Discussion

Optimum inulation thickness for heating load ranges between 0.011 m and 0.11 m for different structural elements and insulation materials (Figure 2-a). The highest result for heating is calculated for R-RW while lowest value is calculated for EW-XPS. For all of the structural elements, RW presents the highest insulation thickness values and is followed by GW, EPS and XPS respectively. Erzurum presents the highest insulation thickness values with the highest HDD while Antalya presents the lowest values with the lowest HDD.

Optimum insulation thickness values for cooling degree days are only remarkable for Antalya because of its highest cooling degree days (CDD) value (Figure 2-b). Beside it, lower results changing between, 0.002m and 0.011 m are determined for İstanbul province considering GF-RW, GF-GW, R-RW, R-GW, R-XPS and R-EPS. 0.005m and 0.002m insulation thicknesses are also calculated for Ankara province for R-GW and R-EPS respectively.

When heating and cooling loads are taken into consideration together, optimum insulation thicknesses increase for Antalya in comparison with its values that are obtained for only cooling loads (Figure 2-c). Optimum insulation thicknesses for Erzurum do not change with use of heating +cooling loads and obtain same results with only consideration of heating load. Insulation thickness values for İstanbul, Ankara and Sivas also increase with a decreasing difference due to their HDD values.

Tables 4, 5 and 6 present the annual saving, total cost savings over 10 years, fuel consumption and CO_2 emission values for ranging structural elements, insulation materials and provinces for heating and both of heating and cooling loads. For both of the situations with the increasing insulation thickness due to increasing HDD, annual cost and total cost savings increase while fuel consumption and CO_2 emission values decrease. Since insulation thicknesses for both of heating and cooling loads are higher than the ones for only heating load, it presents better annual cost savings with less fuel consumption and CO_2 emissions. For example, CO_2 emission value of R-EPS-İstanbul is 8.001 kg/m^{2}year for heating load and decreases to 7.610 kg/m^{2}year for heating+cooling loads while it is 10.872 kg/m^{2}year for heating load and decreases to 10.820 kg/m^{2}year for Sivas. But total cost savings decrease also beacuse of increasing insulation cost. Erzurum, which is the coldest province presented the same insulation thicknesses, savings and CO_2 emissions for two different calculation method while the difference decreases for other provinces with decreasing HDD.

Calculated CO_2 emission values change due to insulation materials and chosen provinces but is not effected by structural elements' type if the fuel is natural gas as in this study. For example CO_2 emission value for GF-GW, EW-GW and R-GW is equal to 3.994 kg/m^{2}year for Antalya while it is 6.386 kg/m^{2}year, 7.849 kg/m^{2}year, 9.080 kg/m^{2}year and 10.792 kg/m^{2}year for İstanbul, Ankara, Sivas and Erzurum provinces respectively considering both of heating and cooling loads.

In general CO_2 emission values changes between 3.95 -10.634 kg/m^{2}year for RW, 3.994-10.792 kg/m^{2}year for GW, 4.759-12.860 kg/m^{2}year for EPS and 5.797-15.665 kg/m^{2}year for XPS. According to results, RW provides the least CO_2 emission beside less fuel consumption and better annual cost and total cost savings. CO_2 emissions provided by RW is as 3.935 kg/m^{2}year for Antalya, 6.293 kg/m^{2}year for İstanbul, 7.734 kg/m^{2}year for Ankara, 8.947 kg/m^{2}year for Sivas and 10.634 kg/m^{2}year for Erzurum. On the other hand, XPS presentes the highest CO_2 emission values as 15.665 kg/m^{2}year regarding GF-XPS, EW-XPS and R-XPS for Erzurum province because of the highest level of fuel consumption.

4. Conclusion

In this study, CO_2 emissions of different insulation materials have been analyzed considering different structural elements and provinces that represent different climatic regions of Turkey. Analysis made for calculated optimum insulation thicknesses with Degree-Day Method considering heating load, cooling load, both of heating and cooling loads. Natural gas was accepted as fuel for heating and electricity for cooling. Main findings of the study can be listed as below

- The highest insulation thickness for heating load was calculated for R-RW while lowest value was calculated for EW-XPS.
- Optimum insulation thickness values for cooling degree days is only remarkable for Antalya because of its highest CDD values.
- When heating and cooling loads have been taken into consideration together, optimum insulation thicknesses have increased for Antalya in comparison with its values that had been obtained for only cooling loads while the values for Erzurum did not change.
- With increasing insulation thickness, annual cost and total cost savings increased while fuel consumption and CO_2 emission values decreased. But total cost savings decreased because of increasing insulation cost.
- Calculated CO_2 emission values changed due to insulation materials and chosen provinces but not effected by structural elements' type for natural gas.
- For all of the structural elements (GF, EW and R) RW presented the highest insulation thickness values and was followed by GW, EPS and XPS respectively.

RW provided the least CO_2 emission beside less fuel consumption and better annual and total cost savings while XPS presented the highest CO_2 emission values.

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