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Full Length Research Paper

The effects of insulation location and thermo-physical properties of various external wall materials on decrement factor and time lag

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Technological improvements and population growth make energy saving more important especially for developing countries. As known, a considerable amount of consumed energy is used for space heating in buildings; therefore, using insulation for external wall has gained more importance. In this sense, this study, which consists of two parts, examines the efficiency of insulation location and thermo-physical properties of various external wall materials (brick, reinforced and lightweight concrete). In the first part, the optimum insulation thickness of external walls for various wall materials and different fuel types in cold region (Eskişehir) has been investigated. The optimization is based on the P_1-P_2 method. Besides, the effect of the thermal properties of different wall constructions and the location of insulation on time lag and decrement factor are studied; and then, the daily thermal behaviours of various wall constructions are simulated. In consequence of the study, time lags were determined between 4.34 and 6.74 on the outer insulated walls and 3.64 and 5.86 on the inner insulated walls. The decrement factor was computed between 0.008 - 0.023 and 0.019 - 0.029 respectively.

Key words: External wall, time lag, decrement factor, P_1-P_2 method, optimum insulation thickness.

INTRODUCTION

Energy consumption of buildings has a very large proportion in total social energy consumption of Turkey, approximately 37% (Anon, 2008). It is known that the rate of energy consumption is rising rapidly due to population growth, urbanization, consumer tastes, industrial activity, transportation and etc. Population growth means constructing more buildings, which gives rise to energy expenditure. Annual growing ratio of population in Turkey was 1.45% at the end of 2009 (TUIK, 2010). In addition, due to the very limited indigenous energy resources, Turkey has to import approximately 75% of the energy requirement from other countries, and this makes energy saving evident in the country (Anon, 2008; Erdal et al., 2008). As known, building sector plays a significant role in global energy consumption. It is generally admitted that most of the energy loss in building elements arises due to building envelope, which contains walls and roofs. The external walls of a building are the interface between its interior and the outdoor environment. Therefore, using insulation is an option for minimizing the energy loss and for protecting indoor comfort. Application of thermal insulation material on external walls is one of the most effective energy conservation measures in buildings. Energy conservation reduces fuel consumption and its environmental effects such as polluting products. Increasing energy demand and environmental consciousness all over the world entail using energy efficiently. Therefore energy conservation is an important part of any national energy strategy. On the other side, global warming is setting in and is going to change the climate (Sayigh, 1999). In this context, the implementation of the European Directive on the Energy Performance of Buildings (EPBD) is a milestone towards the improvement of energy efficiency in the building sector (Theodosiou and Papadopoulos, 2008). The regulations

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of EPBD have been in force since 5th December, 2009 in Turkey, and the obligation of Kyoto Protocol requires the energy efficiency and reduction of emissions.

As a main part for energy loss, the thermal performance of exterior wall has an important influence on the energy-saving effects of buildings. For providing indoor thermal comfort, the ratio of consumed energy (heating and cooling) may vary in different climate zones. Therefore, wall materials and thermal insulation systems should be chosen according to the characteristics of climate and energy consumption. Thus, by utilizing adequate wall materials, it is possible to optimize the performance of thermal insulation systems which have positive effects on energy efficiency. There are many studies about the estimation of optimum insulation thickness for buildings because of the large potential for energy savings.

Bolattürk investigated the determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey and found out that optimum insulation thicknesses vary between 0.02 and 0.017 m, and energy savings vary between 22 and 79% (Bolattürk, 2006). In another study, life-cycle cost analysis is used to determine optimum insulation thicknesses for two types of insulation materials under the climatic conditions of the Mediterranean region and found savings up to 21 $/m^2 of wall area (Hasan, 1999). Çomaklı and Yüksel computed optimum insulation thicknesses between 0.085 and 0.107 m and energy saving as 12.14 $/m^2 of wall area over a 10 year lifetime for the cities with cold climate (Çomaklı and Yüksel, 2003). In the study, it is stated that the insulation in external walls of buildings has been gaining much more interest in recent years not only for the environmental effect of the consumed energy but also for the high cost of the energy. Generally in foregoing studies and literature, it is emphasized that the optimum insulation thickness depends on the cost of insulation material and cost of energy, as well as cooling and heating loads, efficiency of the heating system, lifetime of building, and current inflation and discount rates.

External wall materials in terms of thermo-physical properties have an effect on energy saving and control the indoor climatic conditions which affect human health and their efficiency. In this context, the effects of thermo-physical properties of wall materials on time lag and decrement factor are investigated by Vijayalaksmi et al. (2006), Asan and Sancaktar (1998) and Yumrutaş et al. (2007). Vijayalaksmi et al. studied the thermal behaviour of building wall elements by using finite difference model, and they compared the result with the experimental findings (Vijayalaksmi et al., 2006). Asan and Sancaktar, in their study, investigated the effects of thermo-physical properties and thickness of a wall of a building on time lag and decrement factor (Asan and Sancaktar, 1998). They emphasized that thermo-physical properties have a very profound effect and they computed this process for different building materials. Yumrutaş et al. calculated time lag and decrement factor using periodic solution of one-dimensional transient heat transfer equation and stated that the thermo-physical properties of a wall have very important effects on decrement factor and time lag (Yumrutaş et al., 2007).

Annual cooling and heating loads change according to different climate zones but the thermo-physical properties of wall construction ought to be taken into consideration in terms of indoor thermal comfort and energy efficiency. Energy conscious building design consists of controlling the thermo-physical characteristics of the building envelope such as thermal transmittance (U-value) (Aste et al., 2009). It is stated that Aste et al. (2009) besides the U-value, the envelope thermal inertia should also be considered. It is also stated that Al-Homoud (2005) “the thermal performance of building envelope is determined by the thermal properties of the materials used in its construction characterized by its capability to absorb or emit solar energy in addition to the U-value of the concerning component including insulation”. In the literature a wide range of estimates existed regarding the energy saving potential associated with the use of an adequate inertia, ranging from a few percentages to more than 80% (Aste et al., 2009).

Therefore, this study aims at investigating the role of thermal inertia of external walls made of brick, lightweight and reinforced concrete in addition to the effect of the position of insulation which is placed in the inner and outer surface of the external wall. For this purpose, six different types of external wall constructions (Figure 1) currently used are selected to determine the optimum insulation thickness for various fuel types in Eskişehir, where the ratio of energy consumption is high. Climatic conditions are the major factors governing the heat load requirements of the buildings. Turkish Standard (TS 825) “Heat insulation rules in the buildings” was established (1998) for calculating the heat load. According to TS 825, four different degree-day (DD) regions have been defined for Turkey (TS 825 Thermal Insulation in Buildings,1998). Eskişehir (Altitude 800 m, Longitude 30°31' E, Latitude 39°46' N) is in the third zone with the value of 3649 heating DD (Table 1) (Buyukalaca et al., 2001). Heating procedure is implemented between October-April periods in this city. In general the fuel types used for heating are mainly coal, natural gas, fuel oil and electricity. The prices and lower heating values of the mentioned fuel types and efficiency of heating systems are displayed in Table 2 (Dosider, 2009; Çoban, 2006; Anon, 1997).

In this study, the optimum insulation thickness for the chosen materials for building external wall is determined by considering the heat conductivity and the cost of the insulation material, average temperature in the region, fuel price, and economical parameter using the P_1-P_2 method. On the other side, the effect of insulation position of the wall on decrement factor and time lag are investigated in view of energy saving and thermal comfort

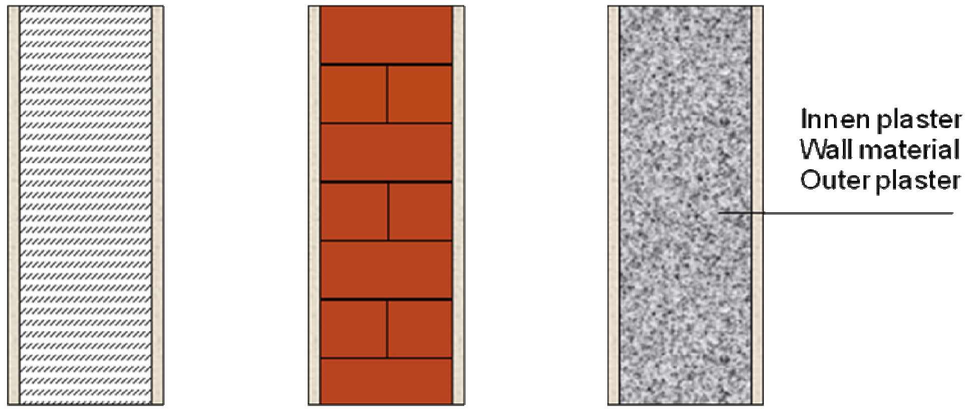

Figure 1. Wall types, constructions and materials with various thermo-physical properties.

Table 1. The climatic data of Eskisehir.

Month	1	2	3	4	5	6	7	8	9	10	11	12	Annual average
Mean daily temperature (℃)	-0.8	1.2	4.6	10.2	15.2	18.7	21.5	21.4	16.9	12.0	7.0	2.4	10.9
Monthly average daily global radiation (MJ m^{-2} day^{-1})	4.48	6.73	9.12	12.53	15.61	17.83	18.38	16.91	13.12	8.99	5.58	3.52	11.07
Maximum temperature (℃)	3.8	5.8	10.7	171	22.0	25.8	28.9	29.2	25.1	20.1	13.1	6.4	17.3
Minimum temperature (℃)	-3.8	-3.4	-1.0	3.3	7.9	10.9	13.3	13.3	9.2	5.0	1.6	-1.3	4.6

Table 2. The parameters used in the calculations.

Parameter	Value			
Degree-days	DD = 3649 ℃ days			
Indoor temperature	20 ℃			
Fuel	Coal	Natural gas	Fuel oil	Electricity
Lower heating value (H)	29.307 MJ/kg	34.541 MJ/m^3	40.612 M J/kg	3.600 MJ/kWh
Efficiency of the heating system (η)	0.60	0.93	0.80	0.99
Price	0.266 $/kg	0.445 $/$m^3$	1.170 $/kg	0.163 $/kWh
Insulation material: Extruded polystyrene	(XPS)			
Conductivity	k =0.028 W/mK			
Density	ρ = 32 kg/m^3			
Price	118.11 $/$m^3$			
Discount rate i	8.63%			
Inflation rate g	5.30%			
P1	8.036			
Lifetime (N)	10 years			

Table 3. Wall structure and thermal characteristics of materials.

Wall types and constructions	Thickness (m)	Thermal conductivity k (W/mK)	Density ρ (kg/m^3)	Specific heat c (J/kg K)	Thermal resistance R (m^{2}K/W)
Wall 1					
External plaster	0.02	0.872	1442	837	0.3174
Heavyweight concrete	0.20	2.000	2400	1060	
Internal plaster	0.02	0.698	1442	837	
Wall 2					
External plaster	0.02	0.872	1442	837	0.3351
Heavyweight concrete	0.20	1.700	2300	920	
Internal plaster	0.02	0.698	1442	837	
Wall 3					
External plaster	0.02	0.872	1442	837	0.3329
Heavyweight concrete	0.20	1.731	2143	840	
Internal plaster	0.02	0.698	1442	837	
Wall 4					
External plaster	0.02	0.872	1442	837	0.8039
Horizontally hollow brick	0.20	0.341	768	781	
Internal plaster	0.02	0.698	1442	837	
Wall 5					
External plaster	0.02	0.872	1442	837	0.7423
Lightweight concrete	0.20	0.381	609	840	
Internal plaster	0.02	0.698	1442	837	
Wall 6					
External plaster	0.02	0.872	1442	837	0.5677
Lightweight concrete	0.20	0.571	609	840	
Internal plaster	0.02	0.698	1442	837	

for inhabitants.

BUILDING MATERIALS AND EXTERNAL WALL STRUCTURE

Brick and varieties of concrete (lightweight and reinforced) are the common materials used for the construction of external walls. But in some cases, depending on the load-bearing characteristics of building and its climate zone, materials and wall construction may vary. External walls are generally constructed as single layered and multilayered. Insulation installation of the walls depends on the type of structure, the type of insulating material used, and its location in the structure (Al-Homoud, 2005). The insulation can be placed to the inside, to the outside or in between (sandwich wall).

In this study, the selected wall constructions and the characteristics of the wall materials (brick, lightweight and reinforced concrete) are demonstrated in Figure 1 and Table 3 (Tsilingiris, 2004; Sambou et al., 2009; Vivancos et al., 2009). The wall is multilayered and consists of plaster on both sides. For calculations, the chosen insulation material is extruded polystyrene (XPS).

HEATING LOAD CALCULATION FOR EXTERNAL WALLS

Energy loss in buildings generally arises through external walls, named building envelope, windows, floors and ceilings, and air infiltration. In this study, as mentioned before, energy loss due to building envelope is taken into account, but not the loss due to infiltration. The annual heat loss from walls in unit area is calculated by the following equation (Hasan, 1999; Yu et al., 2009):

$$q_A = 86400 \cdot DD \cdot U \qquad [1]$$

where *DD* is the degree days, *U* is the overall heat transfer coefficient. The overall heat transfer coefficient is determined by the following equations:

$$U = (R_i + R_w + R_{ins} + R_o)^{-1} \quad [2]$$

where R_i and R_o are the inside and outside air film resistances respectively, R_w is total thermal resistance of the wall layers without insulation, R_{ins} is the thermal resistance of the insulation layer. The thermal resistance of the insulation material is given below:

$$R_{ins} = x / k \quad [3]$$

where *x* and *k* are the thickness and thermal conductivity of the insulation material, respectively. Therefore, U, the overall heat transfer coefficient can be substituted with the following equation:

$$U = (R_{tw} + x/k)^{-1} \quad [4]$$

where R_{tw} is the total wall thermal resistance excluding insulation layer resistance.
When the efficiency of heating system is η, the annual heating energy load is:

$$E_A = \frac{86400 \cdot DD}{\left(R_{tw} + \dfrac{x}{k}\right) \cdot \eta} \quad [5]$$

The parameters used in the calculations are displayed in Table 2.

OPTIMIZATION OF INSULATION THICKNESS AND THE ENERGY SAVINGS

In the present study, the P_1-P_2 method was employed for calculating the optimum insulation thickness (Yu et al., 2009; Duffie and Beckman, 2006; Bacos and Tsagas, 2000). This is a practical, well-known method and can be used for optimizing the thickness of insulation of external walls. P_1 is the ratio of the life cycle fuel cost savings to the first-year fuel cost savings. The equation for P_1 is defined as

$$P_1 = (1 - C\,i)\,PWF(N, i, d) \quad [6]$$

where *i* is inflation rate, *d* is the discount rate, *C* is a flag indicating income producing or non-income producing (1 or 0, respectively). The installation is not income-producing one, so *C=0*. N is the lifetime and assumed to be 10 years. P_2 is the ratio of the life cycle expenditures incurred because of the additional capital investment to be initial investment. The equation for P_2 is defined as:

$$P_2 = D + M_S\,(1 - C\,i)\,PWF(N, i, d) - R_V\,\frac{(1 - C\,i)}{(1 + d)^N} \quad [7]$$

where M_S is the ratio of first year miscellaneous costs (insurance, maintenance) to the initial investment, *D* is the ratio of down payment to initial investment, R_V is the ratio of resale value at end period of analysis to initial investment. Maintenance, insurance, tax savings, resale value are zero in this application. (D = 1, as investment cost paid earlier) P_2 can be taken as 1 in this application.

If an obligation recurs each year and inflates at a rate of i per period, present worth factor (PWF) of the series of N such payments can be found through the following equation:

$$PWF(N, i, d) = \sum_{j=1}^{N} \frac{(1+i)^{j-1}}{(1+d)^j} = \begin{cases} \dfrac{1}{(d-i)}\left[1 - \left(\dfrac{1+i}{1+d}\right)^N\right] & if \;\; i \neq d \\ \dfrac{N}{(1+i)} & if \;\; i = d \end{cases} \quad [8]$$

The building insulation cost is calculated by

$$C_{ins} = C_i \cdot x, \quad [9]$$

The annual heating cost per unit area may be determined by the equation:

$$C_h = \frac{86400 \cdot DD \cdot C_f}{(R_{tw} + \frac{x}{k}) \cdot H \cdot \eta} \quad [10]$$

where *H* is lower heating value of fuel.

The total heating cost of the insulated building is given by

$$C_t = P_1\,C_h + P_2\,C_i\;x \quad [11]$$

Substituting C_h from equation 10 into equation 11 gives the following equation:

$$C_t = P_1\,\frac{86400 \cdot DD \cdot C_f}{(R_{tw} + \frac{x}{k}) \cdot H \cdot \eta} + P_2\;C_i\;x \quad [12]$$

The optimum insulation thickness is obtained by minimizing the equation 12 by which total heating cost is calculated. For this calculation, the derivation of C_t to x is determined and equalized to zero. Thus, the optimum insulation thickness (x_{opt}) is obtained:

$$x_{opt} = \left(\frac{86400\, P_1\, C_f\, DD\, k}{P_2\, H\, C_i\, \eta} \right)^{1/2} - k \cdot R_{tw} \qquad [13]$$

The payback period of insulation cost, N can be calculated through the following equations:

$$N = \frac{\ln\left[1 - \frac{C_i\, P_2\, (R_w^2\, k + R_w\, x)\, H\, \eta\, (d-i)}{86400 DD\, C_f}\right]}{\ln\left(\frac{1+i}{1+d}\right)} \qquad if\ i \neq d \qquad [14]$$

$$N = \frac{C_i\, P_2\, H\, \eta\, (R_w^2\, k + R_w\, x)\,(1+i)}{86400\, DD\, C_f} \qquad if\ i = d \qquad [15]$$

THE EFFECT OF THE INSULATION POSITION OF A WALL ON DECREMENT FACTOR AND TIME LAG

External walls between interior and the outdoor environment are under continuous changing climatic conditions and can be attempted as thermal mass of passive conditioning (heating/cooling) systems. They can manage radiating stored energy to the internal room related to indoor temperature. Energy saving is provided with improved thermal performance through solar energy gain and thermal mass characteristic of the walls. Heat gain from opaque and transparent surfaces of buildings is critically important to determine maximum heat gain and time in external walls. Therefore to provide energy and indoor climate conditions, insulating external walls is inevitable. Moreover, the location and thermo-physical properties of wall layers are important parameters in case of thermal performance of buildings. In this context, time lag and decrement factor are very important thermal inertia parameters to evaluate and interpret the heat storage capabilities of building envelopes. The determination of time lag and decrement factor is valuable primarily in case where there are wide diurnal temperature variations. Furthermore, their determination promotes the design of energy efficient buildings for reducing the heating energy demand. Time lag and decrement factor depend on material properties, thickness and their location in the wall construction (Asan, 2006; Kontoleon and Bikas, 2007; Kontoleon and Eumorfopoulou, 2008; Asan, 1998). The decrement factor is defined as the decreasing ratio of its temperature amplitude during the transient process of a wave penetrating through wall materials. The decrement factor is defined as:

$$f = \frac{T_{wi(\max)} - T_{wi(\min)}}{T_{wo(\max)} - T_{wo(\min)}} \qquad [16]$$

where $T_{wi(max)}$, $T_{wi(min)}$, $T_{wo(max)}$, $T_{wo(min)}$ are maximum and minimum temperatures on indoor and outdoor wall surfaces, respectively. Time lag is defined as the time required for a wave, with period P (24 h), propagate through a wall from the outer surface to the inner surface. The time lag is defined by the following equation:

$$\phi = t_{Twi(\max)} - t_{Two(\max)} \qquad [17]$$

where $t_{Twi(max)}$ and $t_{Two(max)}$ represent the time in hours when indoor and outdoor surface temperatures are at their maximum levels respectively.

The location of insulation is determined by considering maximum time lag and minimum decrement factor. For this purpose, one dimensional transient heat conduction equation is solved using an explicit finite-differences procedure under convection boundary conditions. When the model is established, it is assumed that there is one-dimensional transient heat conduction in wall construction, and governing equation may be written as (Antonopoulos and Valsamakis, 1993; Antonopoulos and Democritou 1993; Ozbalta and Ozbalta, 2010).

$$(\partial T / \partial t) = \alpha * (\partial^2 T / \partial x^2) \qquad [18]$$

where T(x,t) is the temperature, t and x stand for the time and space coordinates, α is the thermal diffusivity. The calculation of the equivalent quantity for a layered wall is given in Appendix (Tsilingiris, 2002).

When the absorption of the solar radiation is taken into account from the energy balance, the heat-flux in the outer surface(x = 0) of the wall is:

$$q_{out}(t, 0) = \alpha_g * I(t) + h_{out} * [T_{out}(t) - T(t,0)] \qquad [19]$$

where I(t) is the total solar radiation incident on the wall surface, α_g is the absorption of the outer wall surface for solar radiation, h_{out} is heat transfer coefficient between the outer surface of wall and outdoor, $T_{out}(t)$ denotes outdoor temperature, T(t,0) is the outer surface temperature. The heat-flux in the inner surface of the wall is;

$$q_{in} = h_{in} * [T(t,L) - T_{in}] \qquad [20]$$

where h_{in} is the heat transfer coefficient between inner space and inner surface of the wall, T_{in} denotes indoor temperature, T(t,L) is the inner surface temperature of the wall. As the initial condition, an arbitrary uniform temperature field is assumed. In this study, the daily thermal behaviours of six basic masonry (brick, lightweight and reinforced concrete) wall constructions are simulated.

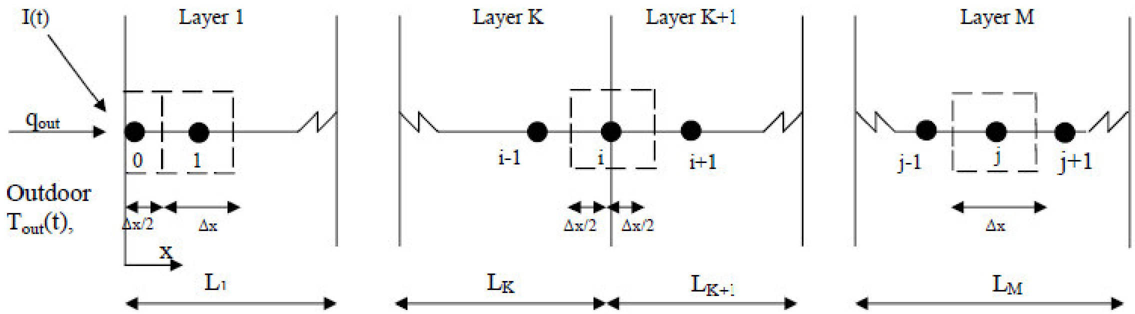

Figure 2. Composite wall of M layers showing node arrangement.

The one-dimensional transient heat conduction equation is solved by employing an explicit finite-differences procedure taking into account the thermo-physical characteristics of the layers. The composite wall of M layers is separated into a number of nodes (Figure 2). Using the energy balance method, the explicit finite-difference equations are derived for the boundary node on the outside surface, interface nodes between layers, interior nodes inside the layers and the boundary node on the outside surface (Al-Sanea, 2002; Ozel and Pıhtılı, 2007). The resulting finite-difference equations are given as follows:

The boundary node (0) on the outside surface:

$$T_0^{p+1} = T_0^p \left[1 - 2\,Fo_1 \left(1 + Bi_1\right)\right] + 2\,Fo_1\,T_1^p + 2\,Fo_1\,Bi_1\,T_S \qquad [21]$$

where $Fo_1 = \alpha_1\,\Delta t / \Delta x$ and $Bi_1 = h_{out}\,\Delta x / k_1$ and sol-air temperature T_S is defined as follows (Kuehn et al., 1998):

$$T_S = T_{out}(t) + \alpha_g\,I(t) / h_{out}\,. \qquad [22]$$

Interface node (i) between layers (K) and (K+1):

$$T_i^{p+1} = \frac{(k_K/\Delta x)T_{i-1}^p + (k_{K+1}/\Delta x)T_{i+1}^p \;\; - T_i^p\,[B + (k_K/\Delta x) + (k_{K+1}/\Delta x)]}{B} \qquad [23]$$

where $B = (\rho_K\,C_K\,\Delta x + \rho_{K+1}\,C_{K+1}\Delta x) / 2\,\Delta t$.

Interior node (j) inside the layer (M):

$$T_j^{p+1} = T_j^p \left(1 - 2\,Fo_M\right) + Fo_M \left(T_{j-1}^p + T_{j+1}^p\right) \qquad [24]$$

where $Fo_M = \alpha_M\,\Delta t / \Delta x$.

The boundary node (n) on the inside surface:

$$T_n^{p+1} = T_n^p \left[1 - 2\,Fo_N \left(1 + Bi_N\right)\right] + 2\,Fo_N\,T_{n-1}^p + 2\,Fo_N\,Bi_N\,T_{in}^p \qquad [25]$$

where

$$Fo_N = \alpha_N\,\Delta t / \Delta x \text{ and } Bi_N = h_{in}\,\Delta x / k_N\,. \qquad [26]$$

The set of the finite-differences equations is solved iteratively by using the Gauss-Seidel iteration method (Incropera and DeWitt, 1996; Ozısık, 1980). Taking the distance between nodal points Δx = 0.01 m, the stability criterion belonging to every layer, has been taken into account in solutions. Hourly changing of temperature distribution in the wall construction is obtained by the explicit approach, and simultaneous solution of the finite-differences equations is written for all nodal points. It is a common practice in air conditioning calculation to use standard values for the indoor and outdoor heat transfer coefficient and for the solar radiation absorption coefficient of the outer surface of the wall; in this study, those values are determined to be 8.141 W/m^{2}K, 23.26 W/m^{2}K and 0.6 respectively in this study (Antonopoulos and Valsamakis, 1993).

RESULTS

The energy loss gets decreased by increasing the insulation thickness on building walls. In consequence of applying insulation, heat load and fuel costs get decreased.

However, increasing the insulation thickness causes the insulation cost to increase. On the other hand, the optimum insulation thickness is proportional with climatic conditions, feature of insulation materials and economic parameters (Çomakli and Yuksel, 2003; Soylemez and Unsal, 1999). The total cost of the much thicker insulation is assumed to increase again than the optimum one. The variation of total cost, fuel and insulation costs in accordance with the insulation thickness is displayed in Figures 3a, b and c for reinforced concrete, brick,

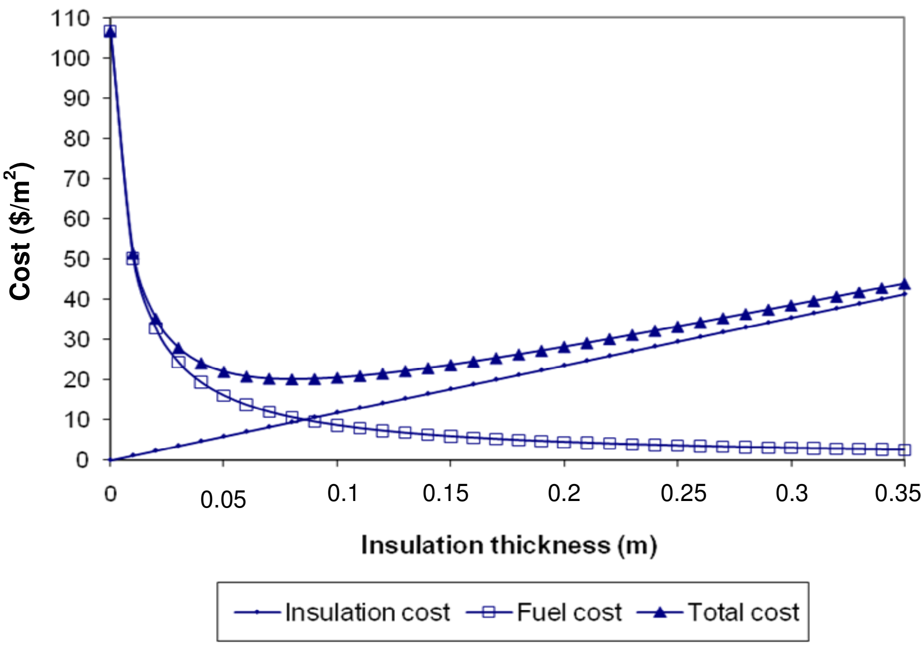

Figure 3a. The effect of insulation thickness on total cost - Wall I reinforced concrete.

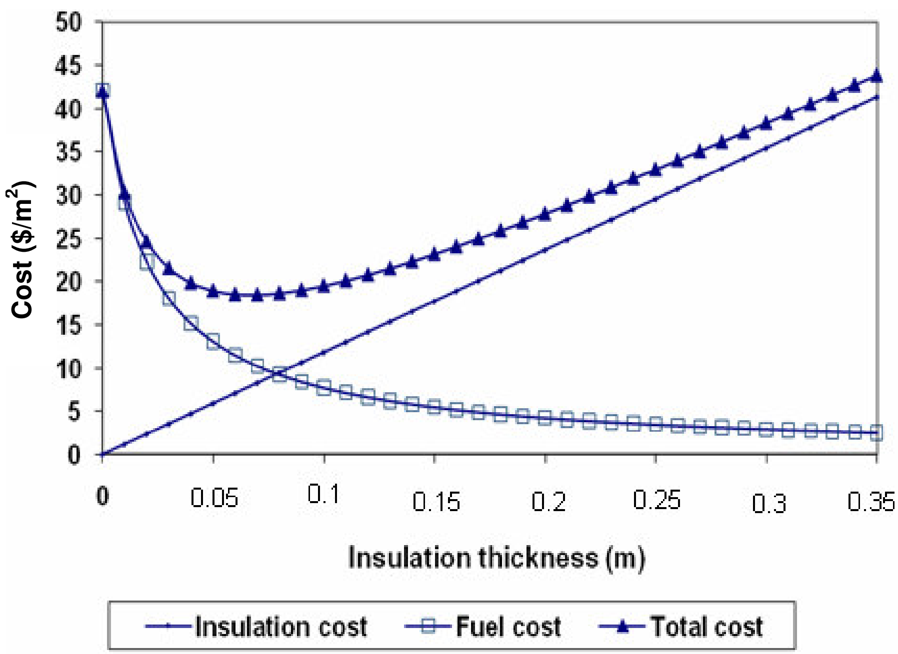

Figure 3b. The effect of insulation thickness on total cost - Wall IV brick.

lightweight concrete walls, respectively and natural gas which are widely used in Eskisehir. The optimum insulation thicknesses of different wall types were calculated by equation 13. The results for different fuel types and for insulation material are shown in Table 4. It was found out that the optimum insulation thicknesses for investigated wall materials vary between 0.082 - 0.157 m for reinforced concrete wall, 0.069 - 0.143 m for brick wall and 0.070 - 0.150 m for lightweight concrete wall.

Since discount and inflation rates affect P_1, the optimum insulation thickness is affected by the mentioned economical criteria. When thermal resistance

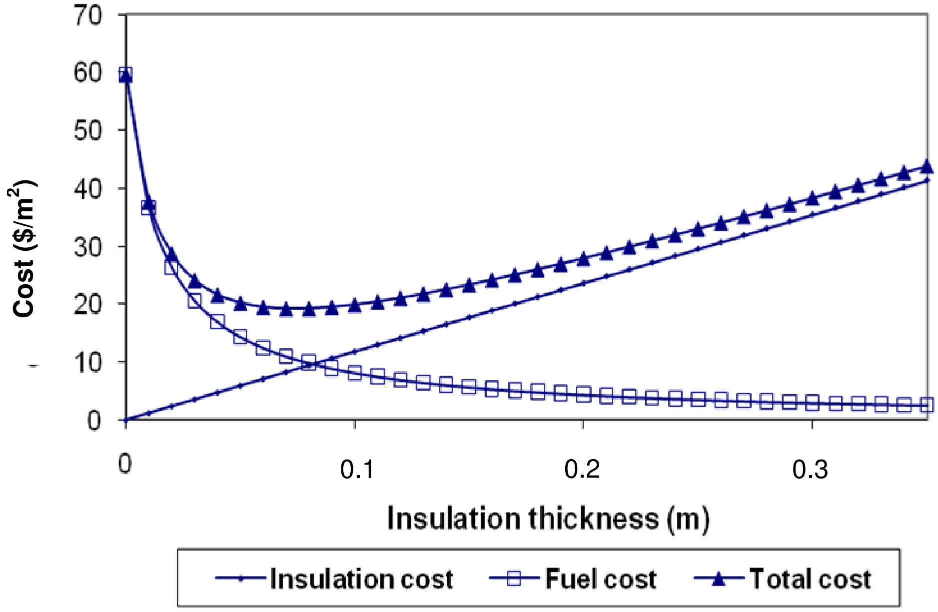

Figure 3c. The effect of insulation thickness on total cost - Wall VI lightweight concrete.

Table 4. The optimum insulation thickness, energy saving and payback period for different fuel and wall types.

Wall type	Optimum insulation thickness for XPS (m)				Energy saving for XPS ($/m²)				Payback period for XPS (years)			
	Coal	Nat gas	Fuel oil	Elect.	Coal	Nat gas	fuel oil	Elect.	Coal	Nat gas	Fuel oil	Elect.
1	0.0864	0.0823	0.1382	0.1569	13.6168	12.4196	33.6017	43.0053	0.8118	0.8485	0.5237	0.4642
2	0.0859	0.0818	0.1377	0.1564	12.8258	11.6948	31.7181	40.6119	0.8575	0.8964	0.5530	0.4902
3	0.0860	0.0819	0.1377	0.1564	12.9159	11.7773	31.9325	40.8844	0.8520	0.8906	0.5495	0.4871
4	0.0728	0.0687	0.1245	0.1433	4.5287	4.0923	11.9590	15.5054	2.0971	2.1941	1.3433	1.1888
5	0.0745	0.0704	0.1263	0.1450	5.0206	4.5429	13.1303	16.9937	1.9316	2.0207	1.2384	1.0962
6	0.0794	0.0753	0.1312	0.1499	6.9963	6.3533	17.8354	22.9722	1.4947	1.5634	0.9597	0.8498

of wall construction in a determined degree-day gets increased, the insulation requirement gets decreased (Tables 3 - 4). The optimum insulation thickness increases in the countries such as Turkey where fuel cost is high. However, applying optimum insulation thickness on external walls provides significant energy saving.

Annual saving per meter square of external wall area was computed as the difference between the cost of heating the insulated and uninsulated buildings. Energy saving depends on fuel cost, climatic conditions and thermal characteristics of external wall materials. The effect of different energy types on energy savings is presented in Figures 4a, b and c. Table 4 illustrates the annual saving obtained by the application of the optimum insulation thickness on external wall rather than uninsulated wall. The values vary between 11.695 - 43.005 $/m^2$ for reinforced concrete wall, 4.092 - 15.505 $/m^2$ for brick wall, 4.543 - 22.972 $/m^2$ for lightweight concrete wall when XPS is applied. On the other hand, it is essential to mention here that energy saving is more important for the expensive fuels such as electricity and fuel oil. The payback periods for different walls and fuel types are also shown in Table 4. The values vary between 0.464 - 0.896 years for reinforced concrete wall, 1.343 - 2.194 years for brick wall, 0.850 - 2.021 years for lightweight concrete wall. With respect to payback period, the lowest value is obtained from reinforced concrete walls.

When the evaluation is done by taking the thermal characteristic of wall materials into consideration, it is seen that (Tables 3 and 5) time lag and decrement factor change between 6.744 - 6.143 h and 0.0082 - 0.0107 respectively for the reinforced concrete walls (Wall 1 - 3) whose heat storage capacity (1745.593 - 1285.671 kJ/m^3K) is high and thermal diffusivity ($0.597*10^{-7}$-$0.810*10^{-7}$ m^2/s) is low. The values for time lag and decrement factor of the brick wall (Wall 4) was found out to be 5.743 h and 0.0176 respectively whose heat storage capacity is 560.061 kJ/m^3K and thermal diffusivity is $1.783*10^{-7}$ m^2/s. For the lightweight concrete walls

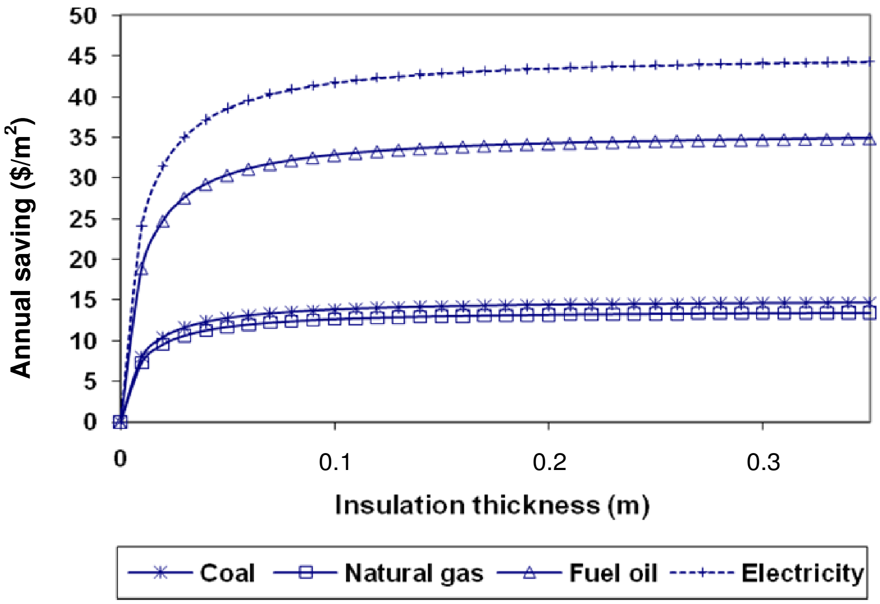

Figure 4a. For different fuel types, the variation of annual saving with regard to insulation thickness - Wall I reinforced concrete.

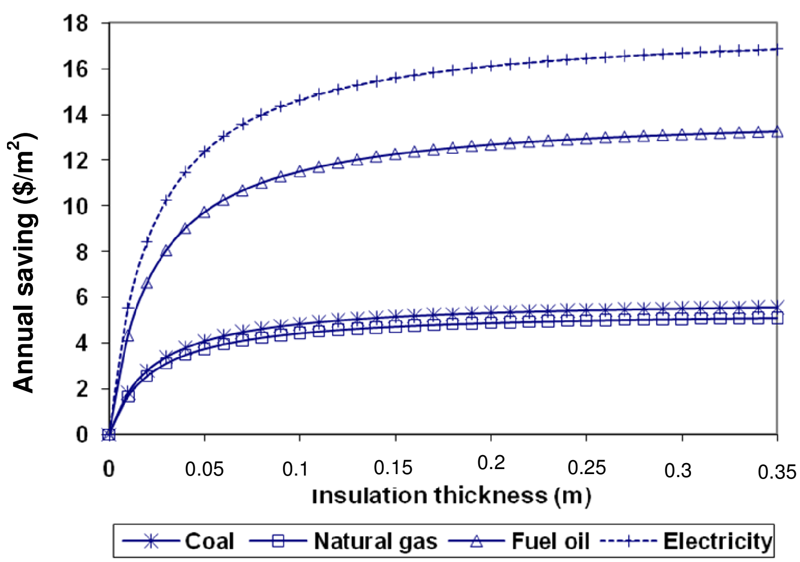

Figure 4b. For different fuel types, the variation of annual saving with regard to insulation thickness - Wall IV brick.

(Wall 5 - 6), time lag and decrement factor vary between 4.343 - 4.963 h and 0.0227 - 0.0204, respectively; heat storage capacity (493.765 - 500.475 kJ/m^3K) is low and thermal diffusivity ($2.065*10^{-7}$ - $2.006*10^{-7}$ m^2/s) is high. All values displayed above for time lag and decrement factor belong to the insulated wall on which insulation is placed in the outer surface of the walls. For the insulated wall on which insulation is placed in the inner surface of external wall, time lag and decrement factor vary between 5.244 – 5.856 h and 0.0194 - 0.0224 for reinforced concrete walls (Wall 1 - 3), 5.000 h and 0.0224 for brick wall (Wall 4), 3.642 - 4.309 h and 0.0289 - 0.0224 for lightweight concrete walls (Wall 5 - 6), respectively.

It seen that thermal mass has maximum efficiency when insulation is placed in the outer surface of external wall in heating season. Furthermore, from outside climatic condition, isolated thermal mass is directly in

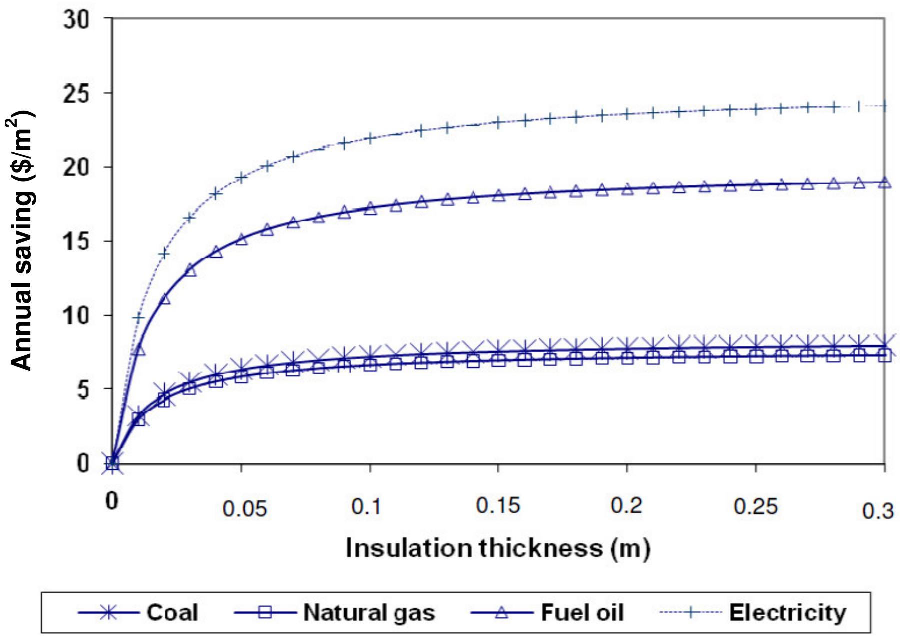

Figure 4c. For different fuel types, the variation of annual saving with regard to insulation thickness - Wall VI lightweight concrete.

contact with the indoor conditioned air, whereby it gained higher inner surface temperature. Thus, it contributes positive effect to the thermal comfort. Besides, outer insulated external wall has better ability to reduce inner surface temperature fluctuations due to thermal capacity of wall materials.

When insulation is placed in the inner surface of external wall, it is seen that thermal mass has less effective utilization. Because thermal mass is isolated from the indoor conditioned air and is exposed to the outside climatic conditions as ambient temperature, wind and humidity etc (Tavil, 2004).

In this study (Vijayalaksmi et al., 2006), it was found out that decrement factor values are lower and time lag values are longer for the walls with insulation on the exterior side. If time lag is longer, the temperature fluctuation on the inner surface is delayed in comparison with the outer surface; and hence, heat can be penetrating into the indoor space the desired time by suitably selecting the wall material. The decrement factor indicates the reduction in amplitude of the inner surface temperature fluctuation. The lower decrement factor is desirable, because the inner surface temperature can be maintained fairly at the constant temperature irrespective of fluctuating outer surface temperature.

Energy efficiency of external wall depends on not only the position of insulation but also the thermal diffusivity and heat capacity of the wall materials. As displayed in Table 5, the increase in heat storage capacity affects the time lag and decrement factor positive, which means increasing time lag, decreasing decrement factor. Hence, the ability of the material is to store more heat so as to delay the heat conduction. The higher thermal diffusivity increases the heat conduction rate and, thus, reduces the time lag and increases the decrement factor. The time lag and decrement factor are affected by the thermo-physical properties of wall material and their position. As a result, to obtain energy efficient external walls, it is necessary to combine different materials so as to get effective thermal diffusivity and heat storage capacity as the best option.

CONCLUSIONS

In this study, the optimum insulation thickness, annual energy saving and payback periods are investigated for six different types of external walls, for XPS as insulation material and four various fuel types for Eskisehir which is one of the coldest cities in Turkey. The calculations are carried out through the P_1-P_2 method over the 10-year lifetime. In consequence of the study, insulation thicknesses were determined between 0.068 - 0.157 m with the amount of 4.1 - 43.0 $/m^2 energy saving and 0.46 - 2.20 years payback period depending on various fuel and wall types. These results show that energy saving is more significant when costly fuel is used. The most suitable fuels for Eskisehir are determined as natural gas and coal.

The position and thickness of each layer in a multi-layered wall construction has significant influences on time lag and decrement factor. The time lag and decrement are very important thermal inertia parameters to evaluate and interpret the heat storage capabilities of building envelopes. The one-dimensional transient heat

Table 5. The effect of wall material properties on the decrement factor and time lag.

	Equivalent thermal conductivity	Equivalent heat storage capability	Equivalent thermal diffusivity	Outer	Insulation	Inner	Insulation
	k_{eq} (W/mK)	k_{eq} (W/mK)	α_{eq}*10^7 (m^2/s)	Decrement factor	Time lag (h)	Decrement factor	Time lag (h)
Wall 1	0.1042	1745.5925	0.5972	0.0082	6.7442	0.0194	5.8558
Wall 2	0.1041	1482.1922	0.7023	0.0095	6.3426	0.0206	5.6226
Wall 3	0.1041	1285.6705	0.8097	0.0107	6.1432	0.0224	5.2442
Wall 4	0.0998	560.0613	1.7827	0.0176	5.7426	0.0224	5.0000
Wall 5	0.1004	500.4751	2.0060	0.0204	4.9635	0.0224	4.3094
Wall 6	0.1020	493.7646	2.0654	0.0223	4.3426	0.0289	3.6416

conduction equation is solved by employing an explicit finite-differences procedure by taking the thermophysical characteristics of the layers into account. It was found out that time lag vary between 4.34 - 6.74 on the outer insulated walls and 3.64 - 5.86 on the inner insulated walls. The least decrement factor was computed between 0.008 - 0.023 and 0.019 - 0.029, respectively. As a result, for the effectiveness of the thermal mass, insulation should be placed on the exterior of external walls. The large heat storage capacity increases time lag and decreases decrement factor. Higher thermal diffusivity decreases time lag and increases decrement factor. The result of this study would be useful for the design of energy efficient buildings.

NOMENCLATURE

Bi, Biot number; **C,** flag indicating income producing or non-income producing; $\mathbf{C_i}$, insulation material cost \$/m^3; $\mathbf{C_f}$, fuel cost (\$/kg, \$/m^3, \$/kWh); $\mathbf{C_h}$, annual heating cost per unit area (\$/m^2); $\mathbf{C_{ins}}$, building insulation cost (\$/m^2); $\mathbf{C_t}$, total heating cost of insulated building (\$/m^2); **D,** down payment fraction; **d,** discount rate; **DD,** degree-days (℃-days); $\mathbf{E_A}$, annual heating energy (J/m^2 year); **f,** decrement factor (-); **Fo,** Fourier number; **H,** lower heating value of fuel depending on the fuel type (J/kg, J/m^3, J/kWh); **h,** convection heat transfer coefficient (W/m^2 K); **I,** inflation rate; **k,** thermal conductivity (W/mK); $\mathbf{M_F}$, fuel consumption; $\mathbf{M_S}$, ratio of first year miscellaneous costs to the initial investment; **N,** lifetime (year); $\mathbf{P_1}$, ratio of the life cycle fuel savings to first-year fuel energy cost; $\mathbf{P_2}$, ratio of owning cost to initial cost; **PWF,** present worth factor; **R,** thermal resistance (m^2 K/W); $\mathbf{R_i}$, inside air-film thermal resistance (m^2 K/W); $\mathbf{R_{ins}}$, insulation thermal resistance (m^2 K/W); $\mathbf{R_o}$, outside air-film thermal resistance (m^2 K/W); $\mathbf{R_w}$, total thermal resistance of the wall layers without insulation (m^2 K/W); $\mathbf{R_{tw}}$, sum of R_i, R_w, R_o (m^2 K/W); $\mathbf{R_V}$, Ratio of resale value at end period of analysis to initial investment; **T,** temperature (℃); **t,** time (s); $\mathbf{q_A}$, heat loss (J/m^2 year); **q,** heat flux (W/m^2); **U,** overall heat transfer coefficient (W/m^2K); **x,** thickness (m), rectangular coordinate (m); $\mathbf{x_{opt}}$, optimal insulation thickness (m).

Greek letter

α= thermal diffusivity (m^2/s), α_g= solar, absorbtivity (-), ϕ = time lag (h), η =efficiency of the heating system, ρ = density (kg/m^3), Δx=internodal distance (m), Δt=time step (s).

Subscripts

A= annual, eq = equivalent, f= fuel, i= inside, Ins= insulation, o=outside, opt= optimum, t= total, tw= total wall excluding insulation material, w= wall material.

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APPENDIX

Heat capacity represents the wall heat storage capability, is expressed as the mass times the specific heat capacity of the wall. The equivalent heat capacity of a multi-layer wall which is composed from parallel layers of thickness is calculated by the expression (Tsilingiris, 2002):

$$(\rho c_p)_{eq} = \left(\frac{1}{\sum_{i=1}^{n} x_i} \right) \sum_{i=1}^{n} \left(\rho_i \, c_{pi} \, x_i \right)$$

The equivalent thermal conductivity of a multi-layer wall is given by the expression:

$$k_{eq} = \frac{\sum_{i=1}^{n} x_i}{\sum_{i=1}^{n} \left(\frac{x_i}{k_i} \right)}$$

The equivalent thermal diffusivity is a very important property of a multi-layer wall and determines how fast the heat diffuses through the wall materials. The equivalent thermal diffusivity is defined as:

$$(\alpha)_{eq} = \frac{k_{eq}}{\left(\rho c_p \right)_{eq}}$$