



INVESTIGATION OF OPTIMUM INSULATION THICKNESS IN THE WALL WITH AIR-CAVITY AND THE ENVIRONMENTAL ANALYSIS

Meral ÖZEL^{1*} , Serhat ŞENGÜR² , Cihan ÖZEL¹ 

¹ Firat University, Mechanical Engineering Department, Elazığ, Türkiye

² Firat University, Technical Sciences Vocational School, Elazığ, Türkiye

* Corresponding Author: mozel@firat.edu.tr

Article Info

Received: October 2, 2025

Revised: February 27, 2026

Accepted: February 1, 2026

Keywords

Air-Cavity,
Dynamic thermal conditions,
Heating and Cooling transmission
loads,
Economical and environmental
parameters.

ABSTRACT

Making energy efficient designs in building walls can be a solution to reduce increasing building energy consumption and thus environmental pollution. By using insulation and energy efficient building materials, the heating and cooling loads of buildings and therefore fuel consumption and environmental pollution can be significantly reduced. Therefore, this paper goals to evaluate the thermal, economic and environmental effects of walls with air-cavities by considering different wall orientations. The study uses a numerical method called the implicit finite difference procedure to compute annual transmission loads for walls that have and haven't air-cavities during the summer and winter seasons in Elazığ province of Turkey. The conclusions show that the annual cooling and heating loads decline by about 31% for all wall orientations when a 2.5 cm air-cavity is positioned in the center of an uninsulated concrete wall. The study also shows that the effect of the air-cavity on heat transmission loads declines as insulation thickness rises. Additionally, walls incorporating air cavities were analyzed to determine their annual average time lag and decrement factor. To identify the optimal insulation thickness, a cost analysis was conducted using annual transmission loads calculated under dynamic thermal conditions. The findings indicate that the most effective insulation thicknesses for walls with air cavities are 12.4 cm for south-facing orientations, 13.2 cm for north-facing, and 13.4 cm for east- and west-facing orientations. When these optimal values are applied across all orientations, the annual heating energy, fuel consumption, and associated emissions are reduced by 87.3%, 87.9%, and 88.0%, respectively.

1. INTRODUCTIONS

Energy conservation has become increasingly significant as a result of the finite nature of energy resources and the environmental degradation associated with fossil fuel consumption [1]. The demand for energy is rising rapidly across key sectors such as industry, construction, transportation, and agriculture. This escalation is primarily driven by factors including population growth, urbanization, migration toward metropolitan areas, and enhancements in living standards. These developments underscore the urgent need for effective energy management strategies to ensure both environmental sustainability and resource efficiency. The construction sector is the second-greatest energy consumer after the industrial sector [2]. The demand for energy continues to rise globally, and the depletion of fossil fuels used in most power plants is causing higher prices and adverse environmental effects. Energy conservation is thus essential in addition to the utilization of renewable energy sources. Cooling and heating of buildings contribute significantly to energy consumption [3]. Improving the thermal performance of the building envelope is vital in enhancing building energy efficiency and reducing the cost of operating building devices [4]. The building envelope is projected to conserve the interior space from severe climate conditions, both hot and cold, to ensure necessary thermal comfort to building occupants. The design and construction of the building envelope should also aim to minimize the consumed energy by air-conditioner and heating unit, leading to a reduction in adverse environmental impact from power plants [5].

The rising demand for electricity owing to factors such as population increase, urbanization, and the need for comfortable indoor thermal conditions, coupled with the escalating cost of energy and the detrimental impact of energy production on the environment, all necessitate a substantial decrease in energy consumption [6]. The energy consumed for heating in buildings accounts for the maximum proportion, approximately 40%, of the consumed total energy in the residential sector in many countries. Therefore, effective thermal insulation in residential buildings is essential in achieving a considerable reduction in energy consumption for space heating. This is especially significant for countries like Turkey that heavily rely on energy imports. Therefore, minimizing heat losses throughout heating periods and providing thermal insulation in buildings are practical measures that can be taken to reduce energy consumption for heating aim in Turkey [7]. The energy efficiency and thermal comfort of buildings are greatly influenced by the thermophysical feature of the materials which are employed in the construction of the building. Therefore, it is crucial to understand the stationary and transient behaviour of wall elements in building energy simulation. Concrete structures are typically characterized by their thermophysical properties in bulk form, without considering any air cavities present in the construction. However, the presence of air cavities can affect both the heat transfer and heat storage capacity of the concrete. This has been demonstrated in research by [8]. Lighter than masonry walls, cavity walls have better thermal resistance and also provide protection against rainfall in humid climates. Adding insulation materials inside the cavity can further enhance its thermal resistance [9]. The building envelope is a crucial design variable for effective energy saving, and building ingredients, specially walls and roofs, must be projected to function as passive systems throughout the building's lifetime [10]. Proper design and operation of buildings can result in significant energy savings. Thus, building designers have a significant role to play in addressing the energy trouble by making proper design decisions early on for the selection of building constituents. Thermal insulation materials play a critical role, and their utilization is a reasonable first step in decreasing the energy needed to maintain a comfortable interior temperature and acquire energy efficiency [11]. The building envelope plays a fundamental role in reducing energy consumption, with particular emphasis on elements such as walls and roofs, which should be designed to operate as passive thermal systems throughout the building's operational lifespan [10]. Energy efficiency can be significantly improved through the careful planning and management of building systems. Therefore, architects and engineers bear considerable responsibility in addressing energy challenges by making informed decisions about construction materials and systems during the initial stages of the design process. Among the strategies for enhancing energy performance, the application of thermal insulation materials is especially important, serving as an effective and accessible solution for reducing the energy required to maintain indoor thermal comfort [11].

A substantial body of research has focused on identifying optimal insulation thicknesses for external building walls. The majority of these investigations rely on simplified models predominantly the degree-day (DD) or degree-hour (DH) approaches which estimate heat transmission losses under steady-state conditions. In contrast, a limited number of studies adopt more sophisticated dynamic modeling techniques that incorporate variables such as solar radiation and thermal inertia of the building. These studies are listed here for References [12-21]. Other studies that utilize the DD or DH concept include References [1,2,7,22-43].

This study was inspired by the work conducted by Al-Sanea et al. [9], which focused on estimating the optimal insulation thickness for cavity wall configurations; however, their analysis was confined to west-facing walls and was conducted using climatic conditions representative of Riyadh. However, both their study and other studies in the literature did not comprise the economic parameters and environmental effects of the cavity wall for different wall orientations. This study aims to fill the identified knowledge gap, and to significantly reduce the heating and cooling loads of buildings and therefore fuel consumption and environmental pollution by making energy efficient designs in building walls. Thus, the primary aim of this work is to analyze in detail the thermal, economic, and environmental effects of the air-cavity in walls for different orientations using the climate conditions of Elazığ province in Turkey. The study numerically investigates the influence of air-cavity on yearly transmission loads, optimum insulation thickness (OIT), fuel consumption, CO₂ and SO₂ emissions, taking into account summer and winter conditions. The yearly transmission loads are computed numerically for walls with and without air-cavity by the implicit finite difference (IFD) method, taking

into account dynamic thermal conditions to ensure accurate results. The study also calculates economical parameters such as the OIT, energy savings, and payback period by employing life-cycle cost analysis for a concrete wall with air-cavity over a building's lifetime of 20 years. Lastly, the study calculates the environmental parameters for the same wall structure.

2. MATHEMATICAL FORMULATION

The multilayer wall configuration, featuring an air cavity centrally located within a concrete wall, is illustrated in Figure 1. The thermal insulation layer, positioned externally on the concrete wall containing the air cavity, is varied incrementally from 0.5 cm to 15 cm in steps of 0.5 cm. The wall's exterior surface is subjected to time-dependent boundary conditions, including ambient air temperature and incident solar radiation, both of which fluctuate throughout the day. In contrast, the interior surface is maintained at a constant design temperature. The one-dimensional equation related to the transient heat transfer for a composite wall is given in Eq. (1) [14],

$$k_j \frac{\partial^2 T_j}{\partial x^2} = \rho_j c_j \frac{\partial T_j}{\partial t} \quad (1)$$

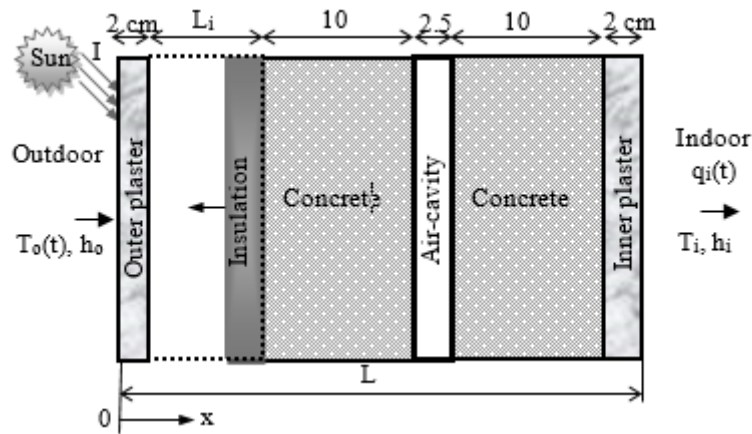


Figure 1. Composite wall structure.

In the equation presented above, T_j represents the temperature, while k_j , ρ_j , and c_j correspond to the thermal conductivity, density, and specific heat capacity of the j th layer, respectively. To obtain a solution for Equation (1), it is necessary to define one initial condition along with two boundary conditions. The initial condition is established by assuming a reference temperature. The boundary conditions at the exterior and interior surfaces of the wall are formulated through Equations (2) and (3), respectively, as outlined in the referenced study [17].

$$-k_p \left(\frac{\partial T}{\partial x} \right)_{x=0} = h_o (T_e(t) - T_{x=0}) \quad (2)$$

$$-k_p \left(\frac{\partial T}{\partial x} \right)_{x=L} = h_i (T_{x=L} - T_i) \quad (3)$$

The external (h_o) and internal (h_i) surface heat transfer coefficients are composed of both convective and radiative components. These coefficients are denoted as h_o for the outer surface and h_i for the inner surface, respectively. Additionally, the sol-air temperature, represented by T_e , accounts for the influence of solar radiation on the outdoor temperature and is incorporated into Equation (4) [44].

$$T_e = T_o + \frac{a I_T}{h_o} - \frac{\varepsilon \Delta R}{h_o} \quad (4)$$

In the above equation, T_o denotes the external environment temperature. I_T and a represent the total incident solar radiation and the solar absorptivity of the external wall surface, respectively. The expression $\varepsilon \Delta R/h_o$ represents the correction factor and is accepted as zero for vertical surfaces. Also, the calculation of I_T for these surfaces is given by Eq. (5) [45].

$$I_T = R_d I_d + (I_y + I_a \rho_y) / 2 \quad (5)$$

The computation procedures of I_T and R_d are in detail provided by Duffie and Beckman [45]. Differential equations and boundary conditions have been previously solved in MATLAB by employing the IFD method, and the temperature distribution along the thickness of the wall was acquired [46].

3. COMPUTATION OF THERMAL CHARACTERISTICS

3.1. Cooling and heating transmission load (CHTL)

This approach of considering a representational day for every month is commonly used in building energy simulations to simplify the calculations while still capturing the seasonal variations in the thermal loads. The twenty first day of each month is often used as a reference day in energy analysis. The aim was to obtain the instantaneous CHTL, which was determined using the following equation [17]:

$$q_i = h_i (T_{x=L} - T_i) \quad (6)$$

The daily total load is acquired by integrating the instantaneous loads over a 24-hour period. Then, the yearly CHTL is separately computed by summing up the daily loads over the entire year.

3.2. Time lag (TL) and decrement factor (DF)

The time lag (TL) refers to the delay experienced by a sinusoidal temperature fluctuation as it travels from the outer surface of a wall to its inner surface. On the other part, the decrement factor (DF) quantifies the extent to which the amplitude of this temperature wave diminishes upon reaching the interior surface, relative to its original amplitude at the exterior. The parameters TL (Φ) and DF (f) are obtained through specific mathematical formulations [46]:

$$\Phi = t_{T_{x=L}(\max)} - t_{T_{x=0}(\max)} \quad (7)$$

$$f = [T_{x=L}(\max) - T_{x=L}(\min)] / [T_{x=0}(\max) - T_{x=0}(\min)] \quad (8)$$

These equations take into account the maximum and minimum temperatures on the indoor and outdoor surfaces of the wall, as well as the times at which these maximum temperatures occur. The TL and DF are computed separately for each month of the year using representative days, and then averaged over the winter period (September-May) and summer period (June-August) to obtain monthly averages. Finally, the yearly average TL and DF are calculated as the arithmetic mean of the monthly averages.

4. THE STRUCTURE OF BUILDING WALLS

Two different wall structures were evaluated for their thermal characteristics, one with an air-cavity and one without. The first wall structure which is without the air-cavity comprises 2 cm external plaster, insulation material, 20 cm concrete, and 2 cm internal plaster. The second wall structure is identical to the first, except that it includes a 2.5 cm air-cavity [12] in the middle of the 20 cm concrete layer, as illustrated in Figure 1. As the insulation material, Expanded polystyrene (EPS) was chosen for both walls, and IT was varied from 0.5 cm to 15 cm. The thermal characteristics of the materials that make up the structure of the walls are listed in Table 1.

Table 1. Thermal characteristics of materials [12, 14]

Material	k (W/m K)	ρ (kg/m ³)	c (J/kg K)	C _i (\$/m ³)
Concrete block	1.730	2243	840	
Expanded polystyrene	0.038	18	1500	188.42
Air	0.167	1.1	1007	
Cement plaster	0.72 0	1860	840	

5. ECONOMIC ANALYSIS FOR OIT

Increasing insulation thickness (IT) in the walls leads to a decrease in air conditioning load and energy costs, but also an increase in the cost of the insulation material. Thus, determining the OIT requires finding the thickness that results in the minimum total cost. In this study, only the transmission part of the air-conditioning load is considered for optimization purposes, as it has the most significant impact on IT [12].

The total cost is defined as the summation of the cost of insulation material and the present value of the energy consumption cost during the building's lifetime. This total cost, evaluated per unit area of the wall, is determined using the following equation:

$$C_t = C_A PWF + C_i L_i \quad (9)$$

The cost of insulation material is denoted by C_i and thickness of insulation is denoted by L_i . The yearly total energy cost and the present worth factor are denoted by C_A and PWF , respectively. Since other loads do not impress OIT, cost optimization is made by taking into account only CHTL. For heating and cooling systems, the yearly total cost of energy is computed separately and is given by [15]:

$$C_A = C_{A,H} + C_{A,C} \quad (10)$$

For heating, the yearly energy cost is determined from the fuel cost (C_F), the total annual heat loss of the wall (Q_l), the lower heating value of the fuel (H_u), and the efficiency of the heating system (η_s) as follows [15]:

$$C_{A,H} = \frac{C_F Q_l}{H_u \eta_s} \quad (11)$$

For cooling, the yearly energy cost is determined from total annual heat gain (Q_g), the cost of electricity (C_E), and the performance of the cooling system (COP) as follows [15]:

$$C_{A,C} = \frac{C_E Q_g}{3.6 \times 10^6 COP} \quad (12)$$

The total cost is determined by taking into account the present worth factor (PWF) over the structure's lifetime of N years. The PWF is influenced by both the inflation rate (g) and the interest rate (i) [22]. The definition of PWF used in this analysis is as follows [22]:

$$PWF = \frac{(1+r)^N - 1}{r(1+r)^N}, \quad \begin{cases} i > g & r = \frac{i-g}{1+g} \\ i < g & r = \frac{g-i}{1+i} \end{cases} \quad (13)$$

$$PWF = \frac{1}{1+i}, \quad i = g \quad (14)$$

The energy savings can be determined by finding the difference between the overall cost of an uninsulated wall and the overall cost of an insulated wall with the optimum thickness. This may be expressed as:

$$S_e = \left(\frac{(Q_l)_{un} \cdot C_F}{H_u \cdot \eta_s} + \frac{(Q_g)_{un} \cdot C_E}{3.6 \times 10^6 \cdot COP} \right) PWF - \left(\frac{Q_l \cdot C_F}{H_u \cdot \eta_s} + \frac{Q_g \cdot C_E}{3.6 \times 10^6 \cdot COP} \right) PWF - C_i \cdot (L_i)_{opt} \quad (15)$$

Where $(Q_g)_{un}$ and $(Q_l)_{un}$ is annual total heat gain and loss in the uninsulated wall (W/m^2), respectively. The payback period (P_b) is calculated by dividing the insulation cost by the annual energy savings and may be expressed as [16]:

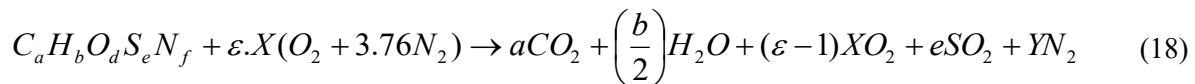
$$PWF(p_b) = \frac{C_i \cdot (L_i)_{opt}}{A_s} \quad (16)$$

In the above equation, A_s denotes the annual energy savings, which is calculated by taking the difference between the energy costs with and without insulation and dividing it by PWF. To incorporate the impacts of inflation and interest rates, the payback period (P_b) can be evaluated using the following expression:

$$P_b = \frac{\ln(1 - r \cdot (C_i \cdot (L_i)_{opt}) / A_s)}{\ln(1 / (1 + r))} \quad (17)$$

6. COMPUTATION OF THE YEARLY FUEL CONSUMPTION AND EMISSIONS

The increment of IT in buildings results in a decrease in heat loss, leading to reduced fuel consumption and emissions that cause air pollution. The general chemical representation of the fuel combustion process is provided as follows [31-37]:



The values of the coefficients X and Y are obtained using the oxygen balance equations presented below:

$$X = \left(a + \frac{b}{4} + e - \frac{d}{2} \right) \quad (19)$$

$$Y = 3.76 \cdot \varepsilon \cdot X + (f/2) \quad (20)$$

In Equation (19), emissions of NOx and CO are excluded from the analysis. The emission rates of CO₂ and SO₂, which are produced from the combustion of 1 kg of fuel, may be calculated using the following equations [37]:

$$M_{CO_2} = (aCO_2) / M \equiv \text{kg } CO_2 / \text{kg fuel} \quad (21)$$

$$M_{SO_2} = (eSO_2) / M \equiv \text{kg } SO_2 / \text{kg fuel} \quad (22)$$

M denotes fuel mol weight and may be computed as follows:

$$M = 12a + 1b + 16d + 32e + 14f \quad \text{kg / kmol} \quad (23)$$

Total CO₂ and SO₂ emissions are determined based on annual fuel consumption as follows:

$$M_{CO_2} = (44a / M) \cdot M_F \quad (24)$$

$$M_{SO_2} = (64e / M) \cdot M_F \quad (25)$$

The annual fuel consumption, M_F is computed as follows [15]:

$$M_F = Q_l / (H_u \cdot \eta_s) \quad (26)$$

7. RESULTS AND DISCUSSION

The study was conducted in Elazığ, Turkey, taking into account wall orientations and climate conditions. Hourly the external environment temperatures were acquired by averaging meteorological data recorded between 2000 and 2014 [47]. Hourly solar radiation at the wall was computed using the isotropic sky model which was proposed by Duffie and Backman [45] and solar radiation which was gauged on the horizontal surface. Indoor air temperatures were kept constant for each month of the year, as presented in Table 2. The external surface solar absorptance was assumed as 0.8, while heat transfer coefficients at the inner side and outer side of the wall were considered as 9 and 22 W/m²K, respectively [48]. Economic and environmental parameters are presented in Table 3.

Table 2. Indoor design temperatures

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sep.	Oct.	Nov.	Dec.
T_i	20°C	20°C	20°C	22°C	23°C	23°C	23°C	23°C	23°C	22°C	20°C	20°C

Table 3. Economic and environmental parameters [49-51]

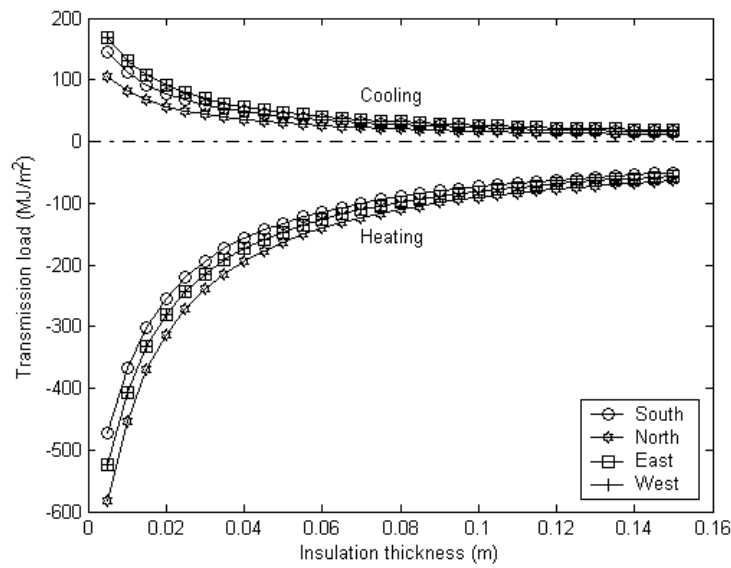
Parameter	Value
Coal (for heating)	
C_F	0.3777 \$/m ³
H_u	29.307*10 ⁶ J/m ³
η_s	% 65
Chemical formula of fuel [37]	C _{7.078} H _{5.149} O _{0.517} S _{0.01} N _{0.086}
Electricity (for cooling)	
C_E	0.1894 \$/kWh
COP	2.5
i	% 8.75
g	% 7.50
N	20

7.1. The Thermal Characteristics of Building Walls

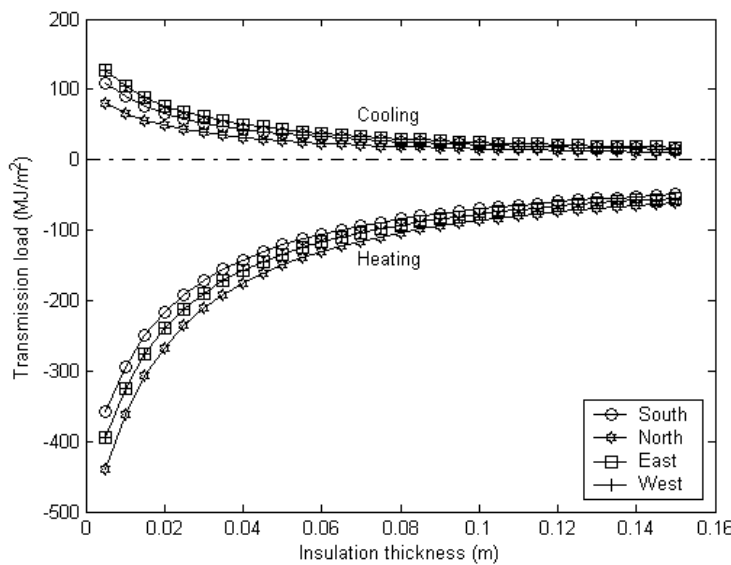
This work employs an IFD method to determine the thermal characteristics of various wall orientations in steady periodic conditions. The focus is on determining the yearly CHTL, as well as the yearly average TL and DF.

Yearly CHTL:

Figures 2(a) and (b) show how the yearly CHTL vary with increasing IT for whole wall orientations. The yearly CHTL for wall structures with air-cavity and without air-cavity at south (S), north (N), and east/west (E/W) orientations are shown in Figure 3(a-c), respectively. As seen from these figures, the E and W orientations provide equal cooling and heating transmission loads. As IT rises, the transmission loads decline and become closer to one another for whole wall orientations. However, when an air-cavity is placed in the wall, the transmission loads decrease more than in walls without air-cavity.



(a)



(b)

Figure 2. (a-b) Variation of yearly CHTL versus increasing IT at all wall orientations for wall structures with air-cavity and without air-cavity.

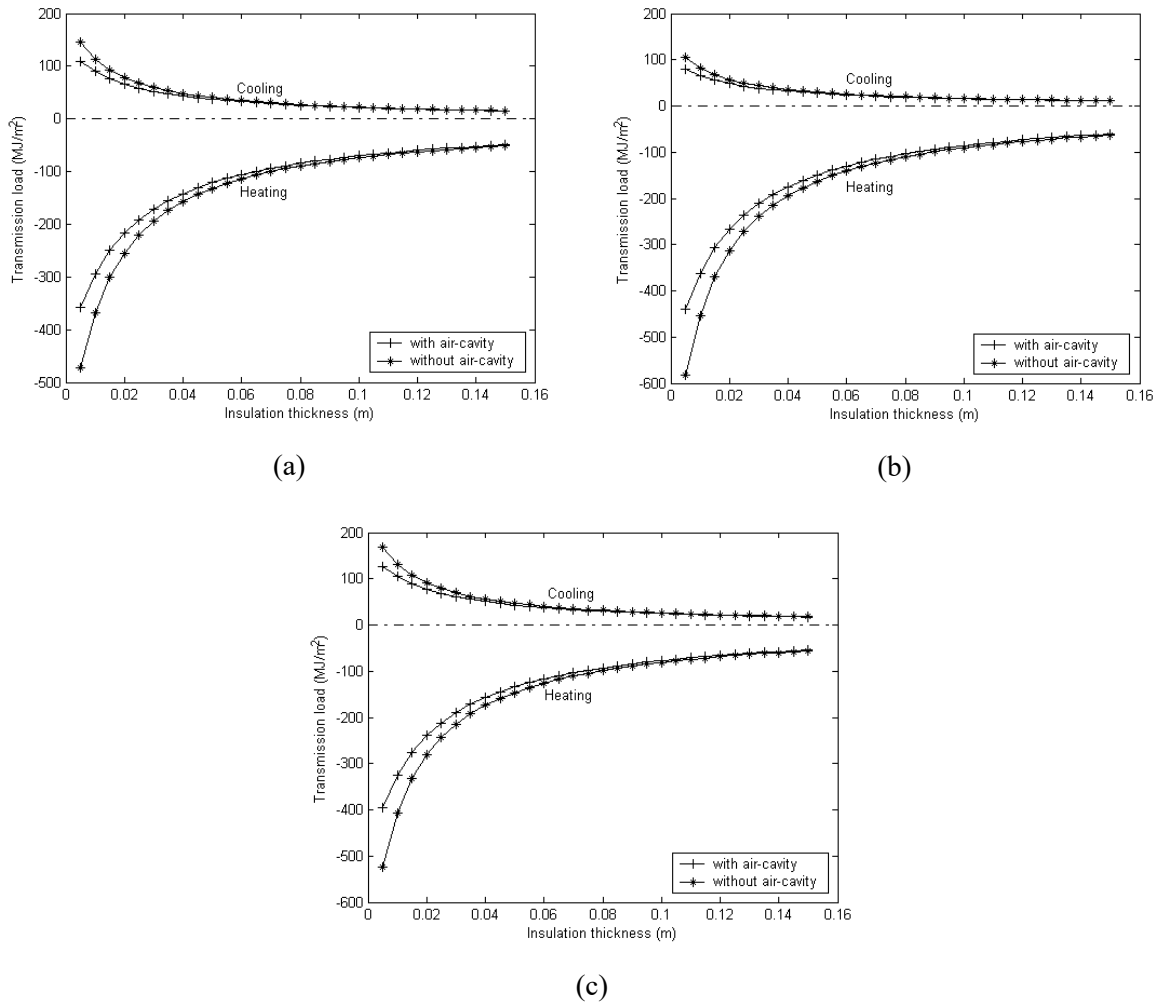


Figure 3.(a-c) Variation of yearly CHTL versus increasing IT for wall structures with air-cavity and without air-cavity at a) S, b) N and c) E/W orientations.

The results indicate that the N-oriented wall has the lowest heating load, while the E/W-oriented wall has the biggest cooling load. Conversely, the S wall has the least heating load and the biggest heating load is acquired for the N wall. It is noted that E and W walls provide equal heating and cooling loads. It is also observed that the heating loads are higher than the cooling loads for whole orientations. These results are consistent with the results of other studies acquired under different climate conditions [13,18,21]. As IT rises, the effect of the air-cavity on transmission loads decreases, as illustrated in Figure 3 (a-c). It is revealed that in the uninsulated wall without air-cavity, yearly cooling loads are 202.88, 148.68, and 236.12 (MJ/m².year) while the yearly heating loads are 663.41, 817.16, and 733.57 (MJ/m².year) for S, N and E/W directions, respectively. Furthermore, it is seen that in the uninsulated wall with air-cavity, yearly cooling loads are 139.27, 102.06, and 162.08 (MJ/m².year) while the yearly heating loads are 455.36, 560.91, and 503.56 (MJ/m².year) for S, N and E/W oriented walls, respectively, as seen in Table 4. When an air-cavity with a thickness of 2.5 cm is positioned in the middle of the concrete wall, the yearly CHTL decrease by about 31% for all wall orientations. The results indicate that air-cavities in walls have a considerable impact on CHTL for uninsulated walls and walls with smaller IT's. It is observed that both with air-cavity and without air-cavity walls provide almost equal yearly transmission loads if the wall is insulated with OIT.

Table 4. The yearly CHTL, the yearly averaged TL and DF for uninsulated wall with air-cavity

Orientation	Transmission loads (MJ/m ² .yr)		Time lag (h)	Decrement Factor
	Cooling	Heating		
South	139.27	455.36	9.64	0.0033
North	102.06	560.92	9.98	0.0031
East	162.09	503.57	12.44	0.0028
West	162.09	503.57	8.64	0.0027

Yearly averaged TL and DF:

In Figure 4, the yearly averaged TL and DF are plotted against IT for whole wall directions in walls with air-cavity. The results indicate that increasing IT brings about a reduction in the DF and an increment in the TL, as expected. Wall orientation has a greater impact on TL than on DF, with the E wall having the tallest TL and the W wall having the shortest as seen in Table 4. While the effect of DF on wall orientations is minimal, the lowest DF is observed in the W wall. But, as IT rises, the DF comes close to each other for all wall orientations.

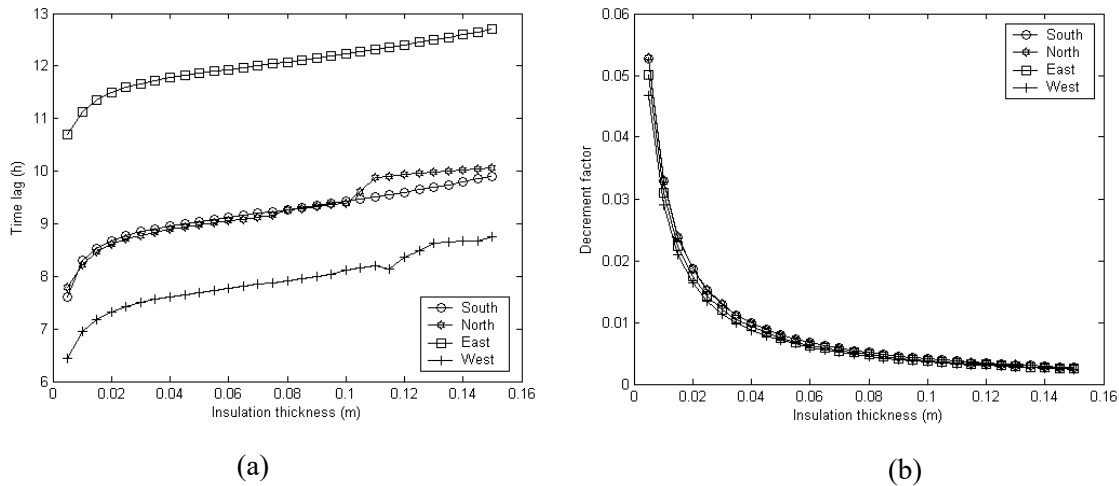


Figure 4.(a-b) Variations of yearly averaged TL and DF with IT for all wall orientations in wall with air-cavity.

7.2. Optimization of Insulation Thickness (IT)

An economic model is utilized to specify the OIT by considering CHTL acquired taking notice of dynamic thermal conditions, as well as the insulation material cost and the present value of consumption of energy during the 20-year lifespan of the building. The cost to IT variations for S, N and E/W walls are depicted in Fig. 5(a-c) for walls with an air-cavity. While the insulation cost rises linearly as IT rises, the energy cost reduces. Total cost is the sum of both costs. The OIT is determined as the thickness that the total cost minimizes. Table 5 provides OIT for whole wall orientations. For walls with an air-cavity, the OIT for S, N and E/W directions are found to be 12.4, 13.2, and 13.4 cm, respectively. It is seen that the E/W walls have the maximum value, while the S wall has the minimum value of the OIT and energy savings.

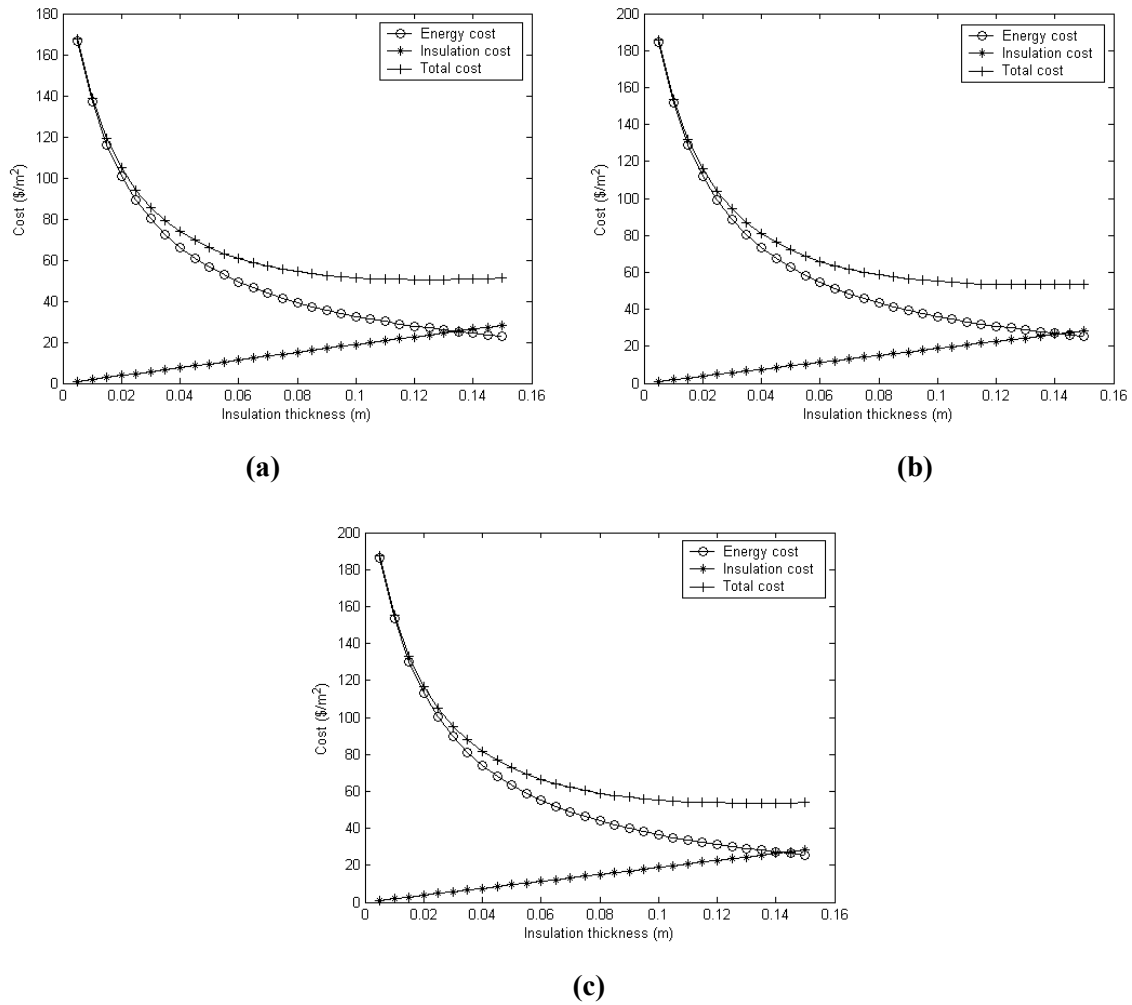


Figure 5.(a-c) Variation of cost to IT for S, N and E (or W) oriented walls, respectively in wall with air-cavity.

Table 5. The OIT, energy savings and payback period for different wall orientations in wall with air-cavity

Orientation	OIT (m)	Energy saving (\$/m ²)	Payback period (years)
South	0.124	161.91	3.04
North	0.132	182.30	2.60
East/West	0.134	184.27	2.94

The results of various studies investigating the influence of wall orientation on the OIT are abstracted in Table 6. It is observed that, for walls with an air-cavity, the S orientation generally requires the least OIT. The findings of the current work are consistent with those of previous studies such as [13,18,21] that investigated different wall structures and climatic conditions, considering heating and cooling loads.

Table 6. The comparison of the other works related to the impact of wall orientation on OIT

Reference study	Location	Insulation material	Optimum insulation thickness (cm)			
			South	North	East	West
Present study (heating+cooling)	Elazığ, Türkiye	Expanded polystyrene	12.4	13.2	13.4	13.4
Ozel [16] (heating)	Kars, Türkiye	Extruded polystyrene	9.2	10.2	9.8	9.8
Ozel [17] (cooling)	Antalya, Türkiye	Extruded polystyrene	3.6	3.1	4.0	4.0
Ozel [13] (heating+cooling)	Elazığ, Türkiye	Extruded polystyrene	5.5	6.0	6.0	6.0
Ibrahim et. al. [20] (heating)	Zahle	Expanded polystyrene	3.4	4.7	3.9	4.0
Ibrahim et. al. [20] (cooling)	Beirut	Expanded polystyrene	4.1	1.9	4.8	4.9
Al-Sanea, Zedan [21] (heating+ cooling)	Riyadh	Molded polystyrene	8.75	8.88	9.2	9.25
Daouas [18] (heating+cooling)	Tunisia	Expanded polystyrene	10.1	10.1	11.7	11.6

The graph in Figure 6 illustrates the impact of IT on energy savings for whole wall directions in a wall with an air-cavity. The data shows that energy savings increase with increasing IT, and reach their maximum at the OIT. The S wall has the least energy savings, while the E/W wall has the maximum. As expected, the energy savings for the E and W walls are identical due to their identical heating and cooling loads. However, the energy savings for the E/W wall and the N wall follow a close curve. The energy savings at the optimum thickness for S, N and E/W directions are 161.91, 182.30, and 184.27 \$/m², respectively.

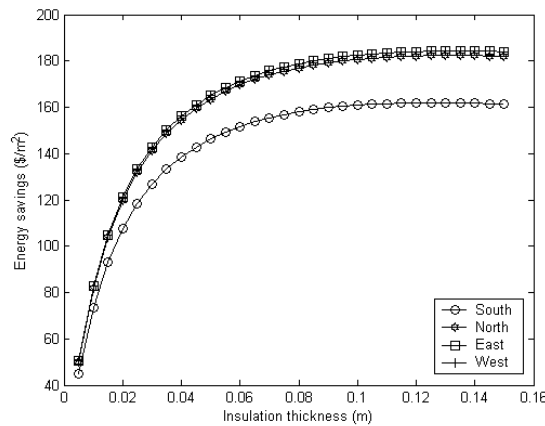


Figure 6. Effect of IT on energy savings according to whole wall orientations.

7.3. The Environmental Analysis

Figure 7 depicts the relationship between yearly fuel consumption, CO₂ and SO₂ emissions, and IT for whole orientations in the wall which has air-cavity. The graphs show that fuel consumption and emissions decrease as IT increases, following a homologous tendency as the yearly heating load. The S wall, which has the least heating load, has the least fuel consumption and emissions, while the N wall, with the maximum heating load, has the highest fuel consumption and emissions. The E and W walls have the same fuel consumption and emissions due to their identical heating loads. When optimal insulation thicknesses are applied for all orientations, the yearly heating load, fuel consumption, and emissions decrease by 87.3%, 87.9%, and 88.0%, respectively, due to the different optimal insulation thicknesses for different wall orientations. These conclusions are in rapport with those acquired by reference [17] using the same dynamic method for a wall without an air-cavity, which showed a reduction in fuel consumption and emissions of 85.5% to 86.7% depending on the wall orientation.

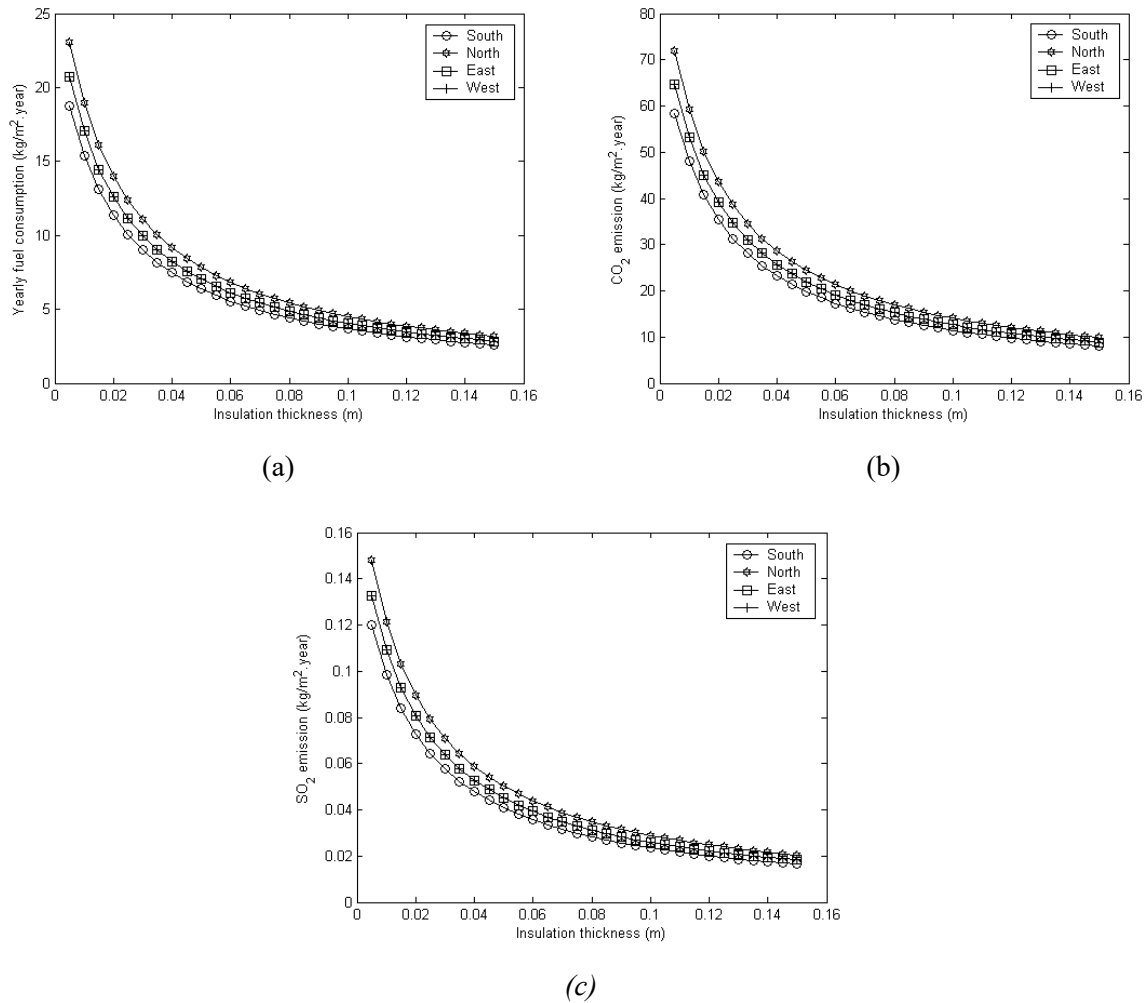


Figure 7.(a-c) Variations of the yearly fuel consumption and, CO₂ and SO₂ emissions with IT for all orientations in the wall with air-cavity.

8. CONCLUSION

The objective of this research is to conduct a numerical analysis of the thermal, economic, and environmental impacts of air-cavities in walls, while taking into account wall orientation and the climate conditions of Elazığ province of Turkey. The study's findings reveal that placing an air-cavity of 2.5 cm thickness in the middle of an uninsulated concrete wall reduces the yearly CHT by 31.35% for all wall orientations. The results indicate that air-cavities in walls have a considerable impact on heating, cooling, and total transmission loads for uninsulated walls and walls with smaller ITs. However, the effect of the air-cavity decreases as IT increases. The research also demonstrates that walls with and without air-cavities provide almost equivalent yearly transmission loads when the wall is insulated with OIT. The study identifies that OITs for the S, N, and E/W orientations of a wall with an air-cavity are acquired as 12.4, 13.2, and 13.4 cm, respectively.

Making energy efficient designs in building walls can be a solution to reduce increasing building energy consumption and thus environmental pollution. The findings of this work provide valuable insights for enhancing energy efficiency in the design of exterior building walls. Furthermore, by promoting reduced fuel consumption and lowering emissions, the outcomes contribute to broader efforts in combating climate change. Several results obtained in this study are consistent with findings reported for various climatic zones in existing literature. The applied methodology can also be adapted for use in different building types, including residential and commercial structures. Moreover, this approach may be extended to various climatic conditions and insulation materials, serving as the basis for future research.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

Contributions of the Authors

Meral Özel: Investigation, methodology, software, analyzing and interpreting the data, discussion, writing original draft, review and editing.

Serhat Şengür: Investigation, analyzing and interpreting the data, discussion, writing original draft, review and editing.

Cihan Özel: Investigation, analyzing and interpreting the data, discussion, writing original draft, review and editing.

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