Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000931

Research Article

Thermal analysis and energy requirement of wall and window components for buildings with different orientations

Meral OZEL[1,*], Serhat SENGUR[2]

[1]*Department of Mechanical Engineering, Firat University, Elazig, 23119, Türkiye*
[2]*Technical Vocational School, Firat University, Elazig, 23119, Türkiye*

ARTICLE INFO

Article history
Received: 07 February 2024
Revised: 04 October 2024
Accepted: 04 October 2024

Keywords:
Climate Zones; Energy Requirements; Heat Gain and Losses; Noninsulated Wall and Insulated Wall; Single-Glazing and Double-Glazing

ABSTRACT

This research highlights the importance of wall insulation, type of glazing and glazing area to reduce energy consumption and to ensure thermal comfort in residential buildings. With the appropriate combination of design parameters such as window glass area, glazing type, wall orientation and wall insulation, heating and cooling loads and therefore energy requirements can be substantially reduced. The main goal of this research is to analyze the thermal performance and energy requirements of the wall and window components that can make residential buildings energy efficient, considering building orientations for four cities of Türkiye. Firstly, heat gain and losses through walls and windows are numerically researched. The heat transmission loads through wall are computed employing an implicit finite difference procedure. Secondly, the ratio of window to wall area is also investigated from the transmission loads point of view. Then, heating and cooling energy requirements and costs are also separately determined for walls consisting of single and double-glazed windows. Consequently, it is observed that the orientation, climate conditions, geographical location, type of glazing and insulation have a notable effect on heat transmission and energy requirement. The results also show that the highest heating energy requirement and cost are acquired for the north orientation in Kars, where the heating load is dominant while the highest cooling energy requirement and cost are acquired for the west (or east) orientation in Antalya, where the cooling load is dominant. It is revealed that the double glazing significantly reduces these energy requirements. The results show that this reduction in heating need for Kars is 61.91%, 45.81%, 49.01% and 49.01% for South, North, East and West orientations, respectively. On the other hand, it is seen that this decrease in cooling need for Antalya is 30.45%, 33.30%, 25.17% and 25.17%. Also, the double glazing appears to be more effective at reducing heating demand than at reducing cooling demand. The results acquired in this work will be very beneficial in the selection of glass type and the glazing area, taking into account the wall direction, when designing exterior walls of residential buildings in different climatic zones.

Cite this article as: Ozel M, Sengur S. Thermal analysis and energy requirement of wall and window components for buildings with different orientations. J Ther Eng 2025;11(2):519−549.

***Corresponding author.**
*E-mail address: mozel@firat.edu.tr

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

INTRODUCTION

The building sector uses up 40% of total energy, making it a crucial area of research for improving energy efficiency. Designing energy-efficient buildings that reduce and control energy demands can contribute to sustainable growth [1]. The building envelope is an essential component of any facility as it protects the occupants and maintains suitable indoor environment conditions. The thermal behavior of the building envelope under changing annual outdoor conditions and indoor comfort requirements is defined by the properties of the materials that form its layers [2].

Solar radiation is a significant contributor to the cooling load in buildings, and it is in charge of 40% -70% of the cooling load. Reducing solar heat gain through walls and windows may lead to an essential decline in energy consumption for air conditioning [3]. Heat transfer through transparent surfaces such as window glass differs significantly from heat transfer from opaque surfaces. Since glazed facades are transparent, solar radiation is transmitted directly to the building [4]. While large windows can increase daylight and reduce the use of artificial lighting, they can also allow excessive heat gains or losses into the building, resulting in higher air-conditioning or heating load and energy consumption [5].

Numerous studies have been conducted in the literature regarding the thermal performance of building components. For example, Al-Sanea investigated the thermal performance of various roof types and they found that if the insulation was placed closer to the inner surface of the roof, thermal performance was slightly improved, but exposed the waterproofing membrane to larger temperature fluctuations [6]. Bojic and Loveday studied the impact of layer thickness and distribution on thermal behavior and found that insulation/masonry/insulation structures saved 32-72% more energy for discontinuous heating plant operation compared to masonry/insulation/masonry structures [7]. Shahid et al. analyzed the impact of cooling degree day value and base temperature on the optimum thickness of insulation [8]. Al-Sanea and Zeden researched the impact of the location of insulation on the heat transfer characteristics and found that placing insulation on the outside resulted in smaller load fluctuation and peak load in winter and summer conditions for wall directions [9]. The same authors optimized the insulation layer distribution and thickness under constant periodic conditions for the same thermal mass and investigated the thermal performance of building walls [10]. Additionally, in another study by the same authors, the indoor air-temperature settings were optimized under the climatic conditions of Riyadh [11]. Daouas, Hassen and Aissia used an analytical method based on Complex Finite Fourier Transform to analyse the thermal performance of building walls [12]. In another study, the transient heat transmission through walls and roofs of buildings was acquired by the CFFT technique. The acquired conclusions were compared with the experimental conclusions [13,14]. Aguilar et al. evaluated the thermal performance of four types of glazing in a double-glazed window in the warm climate conditions in Mexico [15]. Saafi and Daouas investigated the energy benefits of Phase change materials (PCM), the cost-effectiveness of their integration into walls, as well as their interaction with thermal insulation and cool roofs [16]. Hou et al. made a small-scale lightweight building and tested its thermal environment in different directions [17]. Al-Absi et al. experimentally investigated the thermal performance of PCM-based panels developed for external surface cladding of walls [18]. Cho et al. studied the current situation of argon gas-filled double-glazed windows and analyzed the actual degree of deterioration from the point of insulation performance through experiments and simulations [19]. Li et al. clarified the deficiencies of existing thermal performance indexes of walls in practical applications from field research tests in the surrounding areas of Lhasa [20]. Awang et al. investigated the thermal performance and energy efficiency of different wall types [21]. Romdhane et al. analysed the influence of integrating two Trombe walls for different climates and under different construction conditions [22]. Ozel conducted a study on the thermal performance and optimal insulation thickness of walls that have different construction materials [23].

In literature, the impact of window-wall ratio on the thermal behavior had been examined by searchers as follows: Kontoleon and Zenginis analyzed the rate of glazing surfaces to the total wall surface for different orientations. They investigated the impact of indoor temperature settings on heat gain or heat loss [24]. The same authors also analyzed the effect of glazing rate, orientations and zone aspect ratio on the heat flux through the surfaces of a building zone [1]. Kontoleon and Bikas investigated how the percentage of glazed openings and the glazing type affect inner ambient temperatures and energy efficiency during both winter and summer climate conditions [25]. Jaber and Ajib analyzed the yearly heating and cooling energy requirements for three climate regions and four window types, taking into account energy and investment costs. They searched the impacts of U-value, orientation and size of the windows on energy demand [26]. Derradji et al. investigated the thermal behavior of a prototype building in Algiers, Algeria, and identified the most effective insulation thickness for external walls that contain windows [27]. Arıcı and Karabay [28] computed the optimum air layer thickness of double-glazed windows using the degree-days method. Özkan and Onan [29] researched the effect of changing the window and wall areas on the building's heating energy need and optimum thickness of insulation employing the P1-P2 method. Memon and Eames compared the expected performance of triple vacuum-glazed windows with that of other types of windows, including single-glazed, air-filled double-glazed, argon gas-filled double-glazed, and air-filled triple-glazed. The impact of changing the window-wall area ratio, ranging from 5% to 59%, on the provided heat and solar energy gain was examined by the authors [30]. Feng et al. used Energy Plus simulation software to investigate the impact of the window-wall rate on the energy consumption of a nearly zero-energy building with different orientations [31]. A study by El-Deep investigated the effect of window-wall rate and thickness of thermal insulation on energy consumption. The study was conducted in three desert cities such as Alexandria, Cairo, and Khargah, as well as a city with a temperate climate, Berlin [32]. Alwetaishi conducted a study to assess the impact of glazing to-wall ratio on different climate zones in Saudi Arabia, including hot and dry, hot and humid, and moderate climate conditions. The study found that the south and east directions received the highest quantity of heat in whole locations. Based on the results, a glazing-to-wall ratio of 10% was suggested for both hot dry and hot humid climate conditions [33]. Yang et al. examined various factors affecting energy consumption in buildings, including orientation, air conditioning system usage, window-wall ratio, and types of windows. They analyzed the impact of these factors on annual heating and cooling energy demands, as well as annual total energy consumption. The findings revealed that increasing the window-wall ratio led to an increase in total energy consumption [34]. Ghiai et al. performed a study to research the relationship between window-to-wall ratio and energy consumption in high-rise office buildings located in Tehran [35]. Shahid and Karimi investigated the building envelope transmittance value with parameters such as orientation, shading devices, projection factor, glass type and window-wall ratio [36]. Alghoul et al. examined the impact of window-to-wall rate and orientation on yearly heating and cooling energy consumption in an office room with simple double-glazed windows in the city of Tripoli [37]. Hee et al. reviewed case studies to provide insights on selecting the appropriate window glazing for optimum daylighting and energy savings in buildings [38]. Ozel studied the impact of the glazing area on the optimum thickness of insulation for varying orientations [39]. Furthermore, Ozel investigated the influence of the glazing area on the thermal productivity of buildings across all wall directions in the climate zone of Elazig, Türkiye [40].

In general, other factors such as wall insulation, building orientation and glazing type need to be considered in addition to the window-to-wall ratio when designing energy-efficient buildings. By optimizing these parameters, it is possible to achieve important reductions in energy consumption and related greenhouse gas emissions, while creating comfortable indoor environments for building occupants. In the literature, there are many works examining the thermal performance of walls and windows separately. However, although there are a few studies on thermal performance and the insulation optimization of the walls containing windows in the literature, these works don't contain the effect of glazing on the heating and cooling energy requirement of buildings under dynamic thermal conditions. The thermal performance of walls which are containing windows was previously investigated by taking into consideration different structure materials under dynamic thermal conditions [41]. However, the previous study focused on four different structure materials (brick, concrete, briquette and autoclaved aerated concrete). The effect of these structure materials on the glazing area from the point of heat transmission was examined for the south façade of the building, regardless of different wall orientations, under only climatic conditions of Elazig, Türkiye. This study aims to fill this knowledge gap and to find the best design features that can make residential buildings energy efficient. With the appropriate combination of design parameters such as window glass area, glazing type, wall orientation and wall insulation, heating and cooling loads and therefore energy requirements can be significantly reduced. Therefore, the primary purpose of this research is to find out the best appropriate combination of design parameters that can make residential buildings energy efficient. This for purpose, the effects of wall, window and glazing area on thermal performance and energy requirements will be analysed separately and in detail, taking into account many parameters such as building orientations, summer and winter climate conditions, geographical location, type of glazing and wall insulation. Several studies in the literature include only a few of these parameters. This work is carried out for four different cities representing four climate regions of Türkiye. Therefore, firstly, heat gain and losses through wall and window glasses are numerically researched under dynamic thermal conditions for four cities such as Antalya, Kars, Izmir and Istanbul representing four climate regions of Türkiye. In literature, the transmission loads through walls and windows are computed by using different methods. In this research, the heat transfer through the wall thickness is computed as uninsulated and insulated using a dynamic method based on an implicit finite difference process in order to obtain highly accurate conclusions. The heat transfer from window glass is also computed thoroughly for two kinds of glazing by taking into consideration both winter and summer climate conditions, with a different method than other authors in the literature. Secondly, the glazing area in the wall from heat gain and loss point of view is separately determined for four different cities and two types of glazing. Then, heating and cooling energy requirements and costs are also separately determined for walls consisting of single and double-glazed windows by considering orientations.

MATHEMATICAL FORMULATION

Heat Transmission Through Wall

To calculate heat transmission through the walls with and without insulation, temperature distribution through the wall thickness must be determined by solving numerically the transient heat conduction equation in a multi-layer wall which is demonstrated schematically in Figure 1. Since

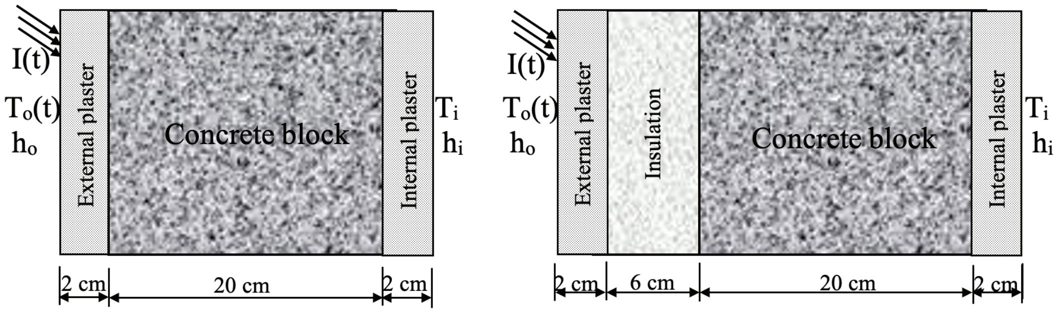


Figure 1. Uninsulated and insulated wall structures.

the thickness of the composite wall is small compared to its width and height, a one-dimensional temperature variation is assumed. One-dimensional equation related to the transient heat transfer may be written as [9]:

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

In the above equation, T_j represents the temperature. k_j, ρ_j and c_j represent the j th layer's thermal conductivity, density and specific heat, respectively. The thermal conduction at the layer's interfaces can be expressed using appropriate equations.

$$T_j = T_{j+1} \tag{2}$$

$$k_j \frac{\partial T_j}{\partial x} = k_{j+1} \frac{\partial T_{j+1}}{\partial x} \tag{3}$$

The wall's initial and boundary conditions are expressed as follows:

$$T_j(x,0) = F_j \tag{4}$$

$$-k_1 \left(\frac{\partial T}{\partial x} \right) = h_o (T_e - T_{es}) \tag{5}$$

$$-k_N \left(\frac{\partial T}{\partial x} \right) = h_i (T_{is} - T_i) \tag{6}$$

The initial condition, F_j represents a uniform temperature that is selected as arbitrary across the wall. T_{es} , T_{is} and T_i represent the outer and inner surface temperatures, and indoor air temperature, respectively. h_o is the external convective coefficient and can be calculated as follows [6, 42]:

$$h_o = 18.63 V^{0.605} \quad \text{in W/m}^2\text{K} \tag{7}$$

Where

$$V = \begin{Bmatrix} 0.25v & for\, v |> 2m/s \\ 0.50v & for\, v < 2m/s \end{Bmatrix} \tag{8}$$

Where v is wind speed, and is taken as 5 m/s [40]. h_i denotes the inner side wall surface's heat-transfer coefficient and is expressed as follows:

$$h_i = h_{c,i} + h_{r,i} \tag{9}$$

Where $h_{c,i}$ and $h_{r,i}$ denote the convective and radiative heat transfer coefficients, respectively. $h_{c,i}$ is taken to be 3.08 W/m^{2}K for heat flow's horizontal direction [40, 42]. $h_{r,i}$=5.72 ε_i W/m^{2}K in relation to a surface emissivity ε_i [40, 42]. It is assumed that the surface emissivity is 0.9 for a building material [6, 40, 42–44]. The sol-air temperature, which combines the effects of solar radiation and outdoor temperature, is represented by T_e and is written for vertical surfaces following as [44]:

$$T_e = T_o + \frac{\alpha_o I}{h_o} \tag{10}$$

Where T_o represents the outside temperature. I and α_o represent the hourly total solar radiation, and the solar absorptivity of the outer wall surface, respectively. The total solar radiation (I) incident upon a surface at any instant may be calculated depending on the slope angle (β) as follows [45]**:**

$$I = I_d R_d + I_y[(1+\cos\beta)/2] + I_a \rho_y [(1-\cos\beta)/2] \tag{11}$$

In the above equation, I_d, I_y and I_a represent instantaneous direct, diffuse and total solar radiations for the horizontal surface. It is assumed that grouninstantaneous direct. R_d is defined for vertical surfaces (β =90^o) following as [45]**:**

$$R_d = [(\cos\delta \sin\varphi \cos\gamma \cos\omega) + (\cos\delta \sin\gamma \sin\omega) - (\sin\delta \cos\varphi \cos\gamma)]/[(\cos\varphi \cos\delta \cos\omega) + (\sin\varphi \sin\delta)] \tag{12}$$

In the above equation, δ, ϕ and ω represent declination angle, latitude angle and hour angle, respectively. To calculate the surface azimuth angle (γ), the orientation of the wall is used. If the wall faces south, then γ = 0°. If the wall faces east, then γ = -90°. If the wall faces north, then γ = ±180°. If the wall faces west, then γ = +90° [45].

To obtain the distribution of temperature along the wall thickness, the differential equation was previously solved in MATLAB employing an implicit finite difference method under dynamic thermal conditions. Detailed calculation procedures are given in references [46, 47]. It has previously been shown in Reference 47 that the numerical solution is in good agreement with the analytical solution. Also, adequate accuracy of the numerical solution obtained by using the implicit finite difference method has been previously obtained as Δx = 2.5 mm and Δt = 60 s according to the place and time steps, respectively [47]. The hourly heat transmission load is determined as follows:

$$q_{iw} = h_i(T_{is} - T_i) \tag{13}$$

Heat Transmission Through Window

The solar radiation and the temperature difference between indoor and outdoor thermal environments cause heat transmission through window glass. Direct, diffuse and reflected solar radiations can come to the outer surface of the window. Some of these radiations are transmitted directly through the glass, some are reflected and some are absorbed. The heat gain (or loss) rate for a single-glazed window as illustrated in Figure 2 is calculated following as [44]:

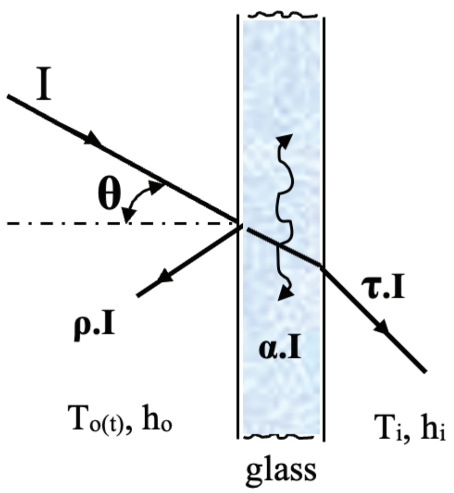


Figure 2. Heat transmission from window with single glass.

$$\begin{aligned} q_{isg} &= F_s\tau_D I_D + \tau_d I_d + \tau_R I_R + \\ &\mathrm{U}.R_o(F_s\alpha_D I_D + \alpha_d I_d + \alpha_R I_R) + U(T_o - T_i) \end{aligned} \tag{14}$$

$$U = 1/(R_i + R_o) = 1/[(1/h_i) + (1/h_o)] \tag{15}$$

In the above equation, F_s represents the sunlit fraction of the window surface. It is assumed that the shading of the window from diffuse sky and reflected radiations may be neglected. The heat gain (or loss) rate for a double-glazed window illustrated in Figure 3 can be computed following as [48–50]:

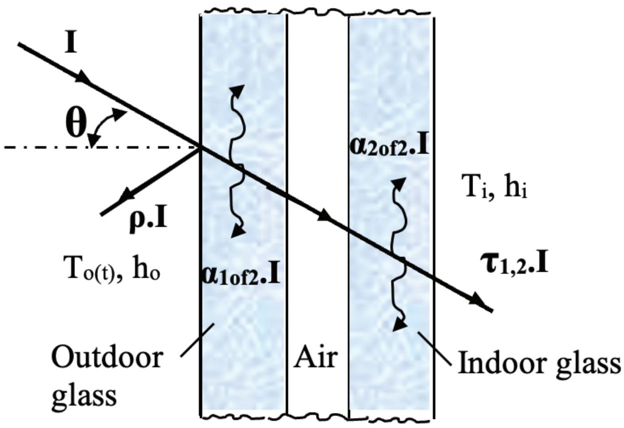


Figure 3. Heat Transmission From window with double glass.

$$\begin{aligned} q_{idg} &= F_s\tau_{(1,2)D} I_D + \tau_{(1,2)d} I_d + \tau_{(1,2)R} I_R + \\ &U.R_o(F_s\alpha_{(1of2)D} I_D + \alpha_{(1of2)d} I_d + \alpha_{(1of2)R} I_R) + \\ &U.(R_o + R_a)(F_s\alpha_{(2of2)D} I_D + \alpha_{(2of2)d} I_d + \alpha_{(2of2)R} I_R) + \\ &U(T_o - T_i) \end{aligned} \tag{16}$$

$$U = 1/(R_i + R_a + R_o) = 1/[(1/h_i) + (1/h_a) + (1/h_o)] \tag{17}$$

In the above equation, h_a denotes the air gap heat transfer coefficient. Separate calculations are required for products τI and αI, since the angles of incidence for direct, diffuse sky and reflected radiations can be different. The transmittance, reflectivity and absorption for a single glass layer are calculated as follows [44, 50, 51]:

$$\tau = \frac{(1-r)^2 a}{1 - r^2 a^2} \tag{18}$$

$$\rho = r + r\frac{(1-r)^2 a^2}{1 - r^2 a^2} \tag{19}$$

$$\alpha = 1 - r - \frac{(1-r)^2 a}{1 - ra} \tag{20}$$

Where r and a represent the fraction of the reflected each component and the fraction of each component available after absorption, respectively. The Component reflectivity r can be found from Fresnel relations. It can be assumed that natural or non-polarized light consists of two components, one vibrating in a plane perpendicular to the glass plane and the other vibrating in a plane parallel to the glass plane. If the components have equal density, r is calculated as [44]:

$$r = \frac{1}{2}\left[\frac{\sin^2(\theta - \theta')}{\sin^2(\theta + \theta')} + \frac{\tan^2(\theta - \theta')}{\tan^2(\theta + \theta')} \right] \quad (21)$$

Where θ is the incidence angle of the sun rays. Its elaborated calculation procedures are available in the reference [45]. The refraction angle θ' is computed as [44]:

$$\theta' = \sin^{-1}(\sin\theta / n) \quad (22)$$

Where n represents the index of refraction. The absorption coefficient which is denoted by a is expressed by [44]:

$$a = \exp[-KL / \sqrt{1-(\sin^2\theta / n^2)}] \quad (23)$$

The extinction coefficient is denoted by a. The thickness of each sheet of glass is denoted by L. In buildings, the use of two separate sheets of glass is general. Parmelee showed that for double glass, the solar heat gain ratio can be expressed as a function of the transmissivity, reflectivity, and absorptivity of each individual sheet of glass. Parmelee has indicated the following for double glazing [44]:

$$\tau_{1,2} = \frac{\tau_1 \tau_2}{1-\rho_1\rho_2} \quad (24)$$

$$\rho_{1,2} = \rho_1 + \frac{\tau_1^2 \rho_2}{1-\rho_1\rho_2} \quad (25)$$

The subscript 1 represents the first glass sheet while subscript 2 represents the second glass sheet. In the calculations of heat transmission, knowing the solar absorption in each glass plate separately is more useful than combining both plates. The absorption coefficient for each sheet can be calculated using the transmissivity and reflectivity.

$$\alpha_{1of2} = \frac{[1-(\rho_1+\tau_1)][1-\rho_2(\rho_1-\tau_1)]}{1-\rho_1\rho_2} \quad (26)$$

$$\alpha_{2of2} = \frac{[1-(\rho_2+\tau_2)]\tau_1}{1-\rho_1\rho_2} \quad (27)$$

The angles of incidence for the direct, diffuse sky, and reflected radiations can be different. For this reason, the incidence angles for the diffuse sky and reflected radiations can be calculated as follows [51]:

$$\theta_d = 59,68 - 0,1388\beta + 0,001497\beta^2 \quad (28)$$

$$\theta_R = 90 - 0,5788\beta + 0,002693\beta^2 \quad (29)$$

Ratio of Window to Wall Area

To research the influence of glazing area on thermal behavior, the total glazing area is determined by accounting for heat transfer through external walls and windows. The window frame area is not taken into consideration in this analysis. When only the glass area is taken into account, the glazing area percentage is calculated as [25, 41]:

$$Glazing\ area\ (\%) = \frac{A_g}{A_t}.100 = \frac{A_g}{A_g + A_w}.100 \quad (30)$$

In the above equation, A_g and A_w represent glass and wall areas, respectively. Using this definition, the transmission loads can be computed for single and double glass with increasing glazing area percentages from 0% to 100% with a 10% increment as follows:

$$Q_i = Q_{isg}.\frac{A_g}{A_t} + Q_{iw}.(1-\frac{A_g}{A_t}) \quad (31)$$

or

$$Q_i = Q_{idg}.\frac{A_g}{A_t} + Q_{iw}.(1-\frac{A_g}{A_t}) \quad (32)$$

In the above equations, Q_{iw} represents the daily total load of wall. Q_{isg} and Q_{idg} represent the daily total loads of single and double-glazed windows, respectively. These loads are calculated by integrating the instantaneous loads provided by equations 13, 14, and 16 over a period of 24 hours. In other words, the daily total load represents the total amount of heat gained or lost by each component over the course of a day.

Heating and Cooling Energy Requirements and Cost

The air-conditioning energy requirement and cost can be substantially reduced with proper use of the thermal insulation, orientations, glazing area and glazing types taking into consideration summer and winter climate conditions. The heating and cooling energy requirements per unit area can be expressed as, respectively:

$$E_h = \frac{Q_l}{COP_h} \quad (33)$$

$$E_c = \frac{Q_g}{COP_c} \quad (34)$$

Where Q_l and Q_g represent the heat loss and gain per unit area of external wall (kWh/m^2) while COP_h and COP_c represent the performance of the air-conditioning system for heating and cooling, respectively. The costs of energy (electricity) per unit area for heating and cooling are calculated following as, respectively:

$$C_h = \frac{Q_l.C_e}{COP_h} \quad (35)$$

$$C_c = \frac{Q_g.C_e}{COP_c} \quad (36)$$

The cost of electricity is denoted by C_e and is taken to be 0.0938 \$/kWh. *COPc* is accepted as 2.5 [27]. It should be noted that COP_c and COP_h are essentially interrelated since $COP_h = COP_c+1$ for vapour-compression systems [52]. Therefore, COP_h is taken as 3.5.

RESULTS AND DISCUSSION

In this research, the impact of wall, window, and glazing area on the building's thermal performance and energy requirements is studied for different orientations. The investigation is conducted in four cities representing Türkiye's four climate zones, considering typical winter and summer conditions on January 15 and July 15, respectively. The first step is to calculate the heat gains and losses through walls and windows, followed by the calculation of heat transmission loads for single and double glazing as the glazing area increases. Finally, the heating and cooling energy requirements and costs are determined.

Environmental Conditions

The research is accomplished for four cities in Türkiye; namely, Antalya, Kars, Istanbul and Izmir. Antalya city (latitude: 36.54°N, longitude: 30.42°E), which is located on the Mediterranean coast of Türkiye, is one of the hottest cities of Türkiye. Kars city (latitude: 40.4°N, longitude: 43.05°E), located in the Eastern Anatolia region of Türkiye, is one of the coldest cities of Türkiye. Istanbul (latitude: 41.0°N, longitude: 28.90°E) is located in Türkiye's Marmara region. Izmir (latitude: 38.2°N, longitude: 27.05°E) is located in Türkiye's Aegean region. The outdoor air temperatures which are supplied by meteorology (Records for weather data 1997-2017) are shown in Figure 4 [53]. The indoor air temperature is accepted as 20°C and 23°C for January and July, respectively.

Figure 5(a-b) and Figure 6(a-b) present the hourly variation of incident solar radiation of Antalya, Kars, Istanbul and Izmir cities for south (S), north (N), east (E) and west (W) orientations in winter and summer conditions, respectively. In winter, it is indicated that for S orientation, maximum solar radiation is obtained to be 448.44, 398.44, 355.10 and 283.70 W/m^2 at 12:00 for Antalya, Izmir, Kars and Istanbul cities, respectively. On the other hand, it is obtained to be 108.28, 100.23, 91.13 and 84 19 W/m^2 at

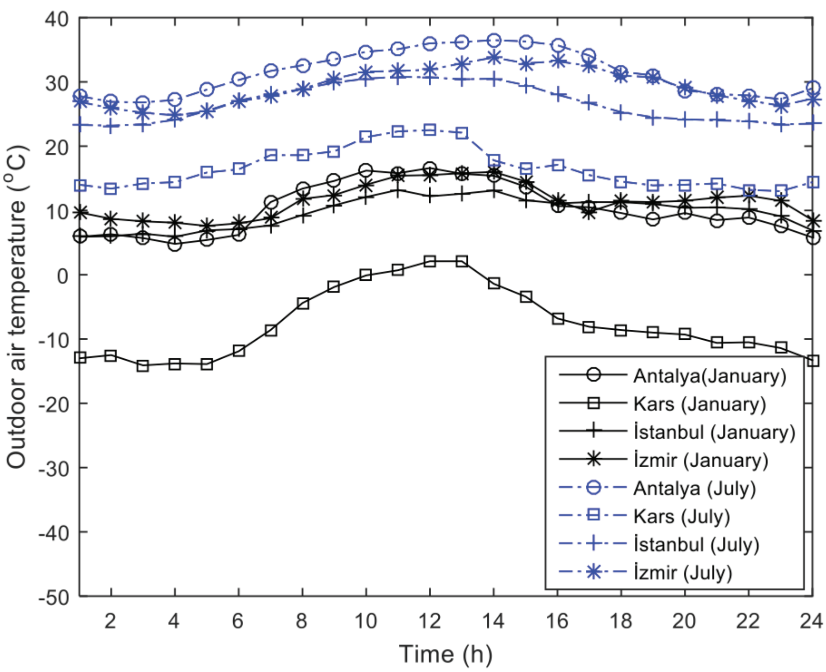


Figure 4. Outdoor air temperatures for four cities in Türkiye in summer and winter conditions.

12:00 for N orientation. It is obtained to be 276.66, 235.09, 204.37 and 154.66 W/m^2 for east and west orientations. But the moment that maximum solar radiation occurs is different. This time is obtained as 9:00 or 10:00 according to cities for the E direction while it is obtained as 14:00 or 15:00 for the W direction. The results indicate that for all orientations, the highest value of maximum solar radiation is obtained for Antalya which has the lowest latitude while the lowest value of maximum solar radiation is obtained for Istanbul which has the highest latitude among examined cities. In summer, it is seen that for S orientation, the maximum solar radiation is obtained to be 381.11, 369.65, 365.99 and 356.95 W/m^2 at 12:00 for Kars, Izmir, Istanbul and Antalya, respectively. On the other hand, it is indicated

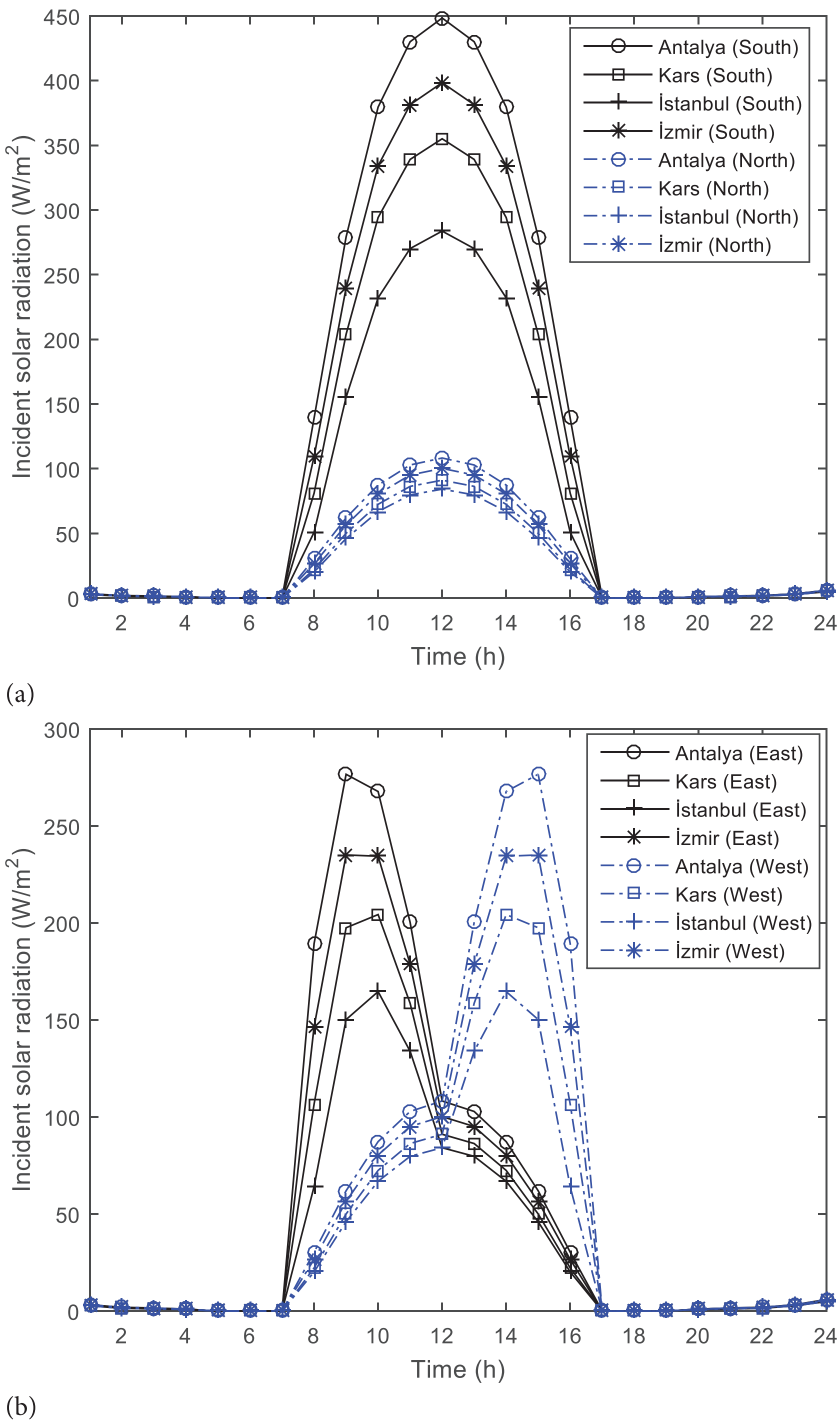


Figure 5. The hourly variation of incident solar radiation of Antalya, Kars, Istanbul and Izmir cities for **a)** south and north orientations and for **b)** east and west orientations in winter conditions.

that for N orientation, maximum solar radiation is acquired to be 189.36, 187.45, 184.50 and 182.12 W/m^2 at 12:00 for Antalya, Izmir, Kars and Istanbul cities, respectively while it is obtained to be 576.07, 572.73, 559.92 and 518.73 W/m^2 for E and W orientations. But, maximum solar radiation occurs at 8:00 for the E direction and at 16:00 for the W direction. The results show that the variation in solar radiation in winter according to provinces is greater than in summer.

Figure 7(a-d) shows the change of sol-air temperatures in January and July months for Antalya, Kars, Istanbul and Izmir, respectively. For Antalya, it is revealed that in winter, the sol-air temperature's maximum peak value is obtained to be 32.91, 20.54, 25.94 and 25.14°C for S, N, E and W

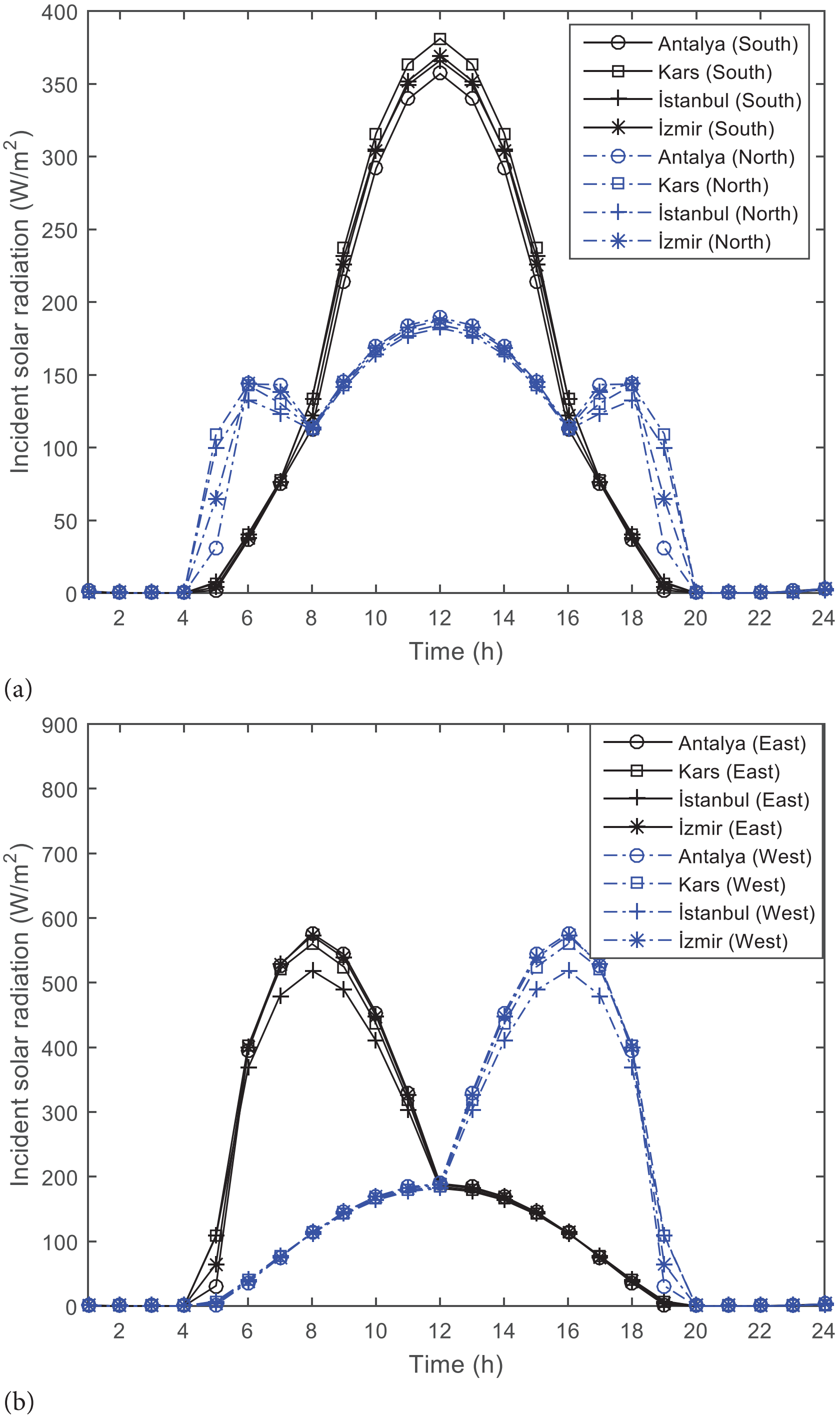
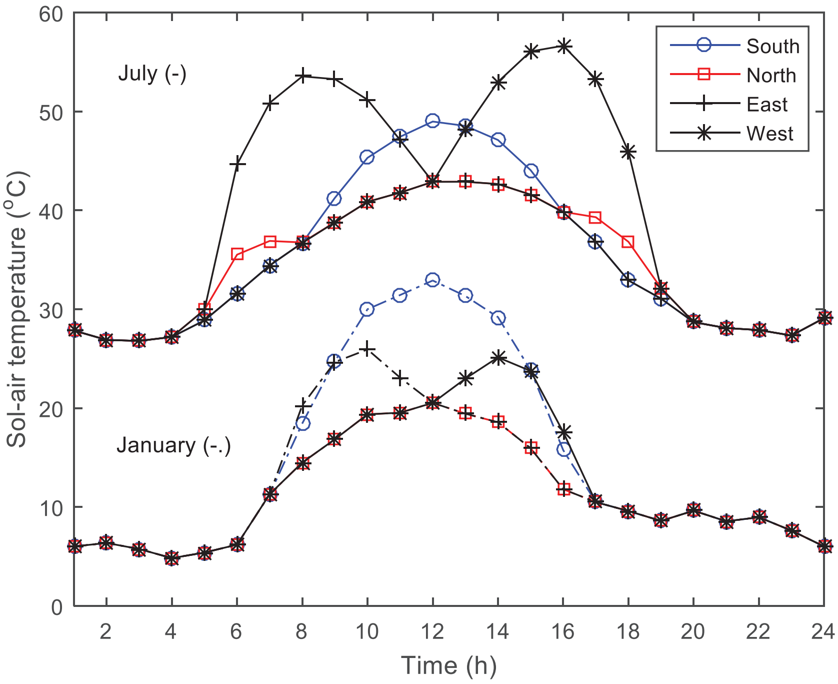


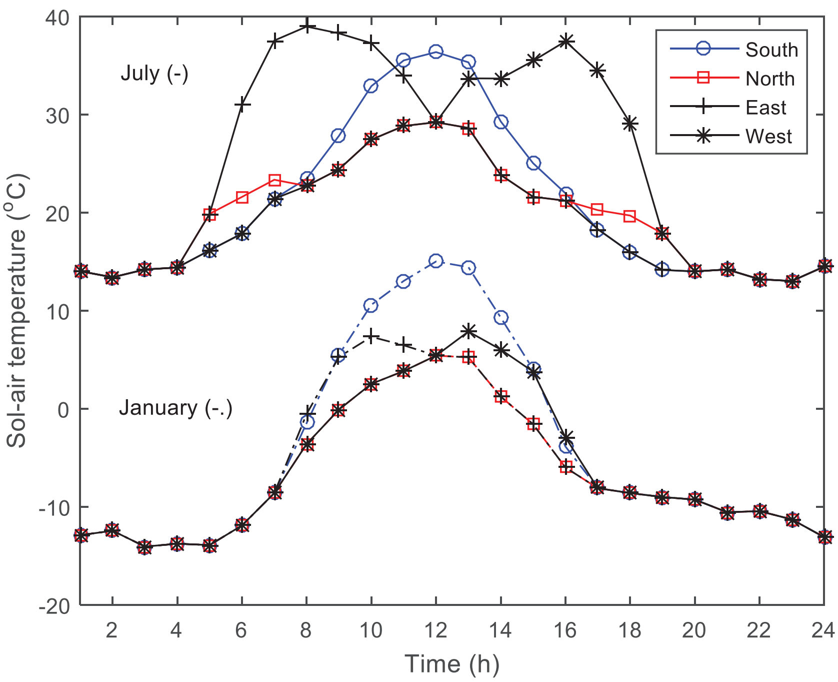
Figure 6. The hourly variation of incident solar radiation of Antalya, Kars, Istanbul and Izmir cities for a) south and north orientations and for b) east and west orientations in summer conditions.

orientations, respectively. On the other hand, in summer, it is obtained to be 48.98, 42.89, 53.55 and 56.65°C. For Kars, it is revealed that in winter, the maximum peak value of sol-air temperatures is obtained to be 15.01, 5.41, 7.33 and 7.87°C while in summer, it is obtained to be 36.36, 29.21, 38.96 and 37.46°C. For Izmir, it is revealed that in winter, the sol-air temperature's maximum peak value is obtained to be 30.00, 19.26, 22.52 and 24.53°C while in summer, it is obtained to be 45.70, 39.91, 50.08 and 54.03°C. For Istanbul, it is revealed that in winter, the sol-air temperature's maximum peak value is obtained to be 23.03, 16.10, 18.09 and 19.09 °C while in summer, it is obtained to be 44.00, 37.32, 47.76 and 47.26°C. The results show that the lowest values of sol-air temperature are acquired in Kars city which has the lowest outdoor temperature.

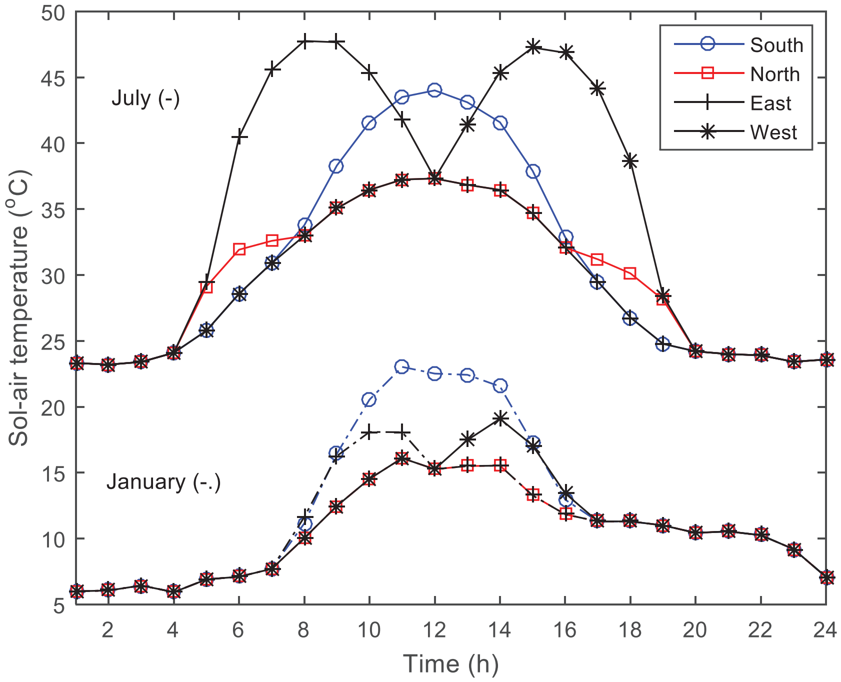
It is obvious that the N orientation gives the least value of sol-air temperature due to the low solar radiation of the north in summer and winter conditions. Also, it is seen that



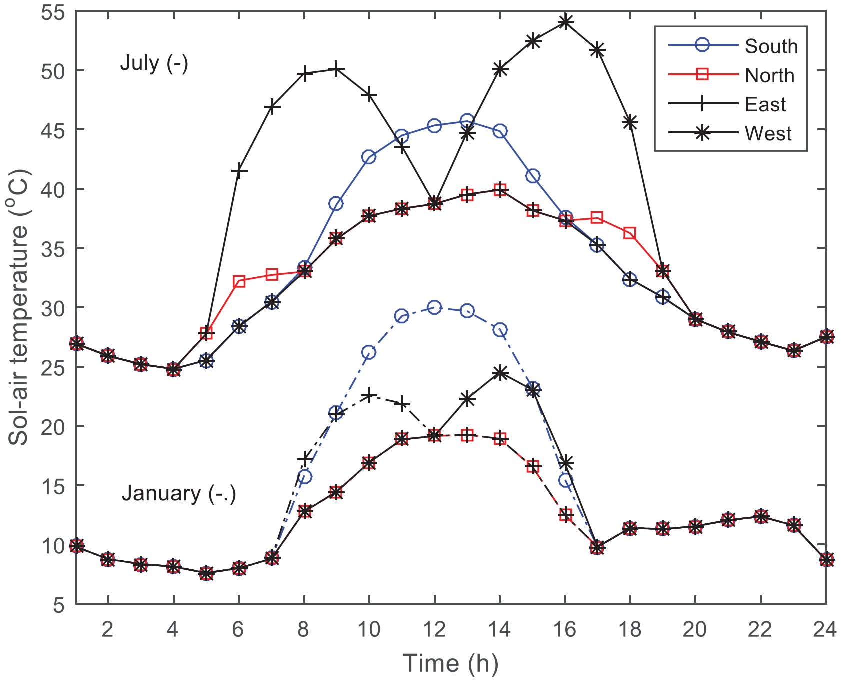
(a)



(b)



(c)



(d)

Figure 7. The hourly variation of sol-air temperature of a) Antalya, b) Kars, c) Istanbul and d) Izmir cities for different wall orientations in summer and winter climate conditions.

in winter, the sol-air temperature's highest value is acquired in the S orientation while in summer, it is acquired in the W or E orientations. This is owing to great solar radiation in the south in winter and in the west or east in summer. These results acquired are found to be in good agreement with those previously reported under different climate conditions [40, 54].

Heat Transmission Loads Through Wall

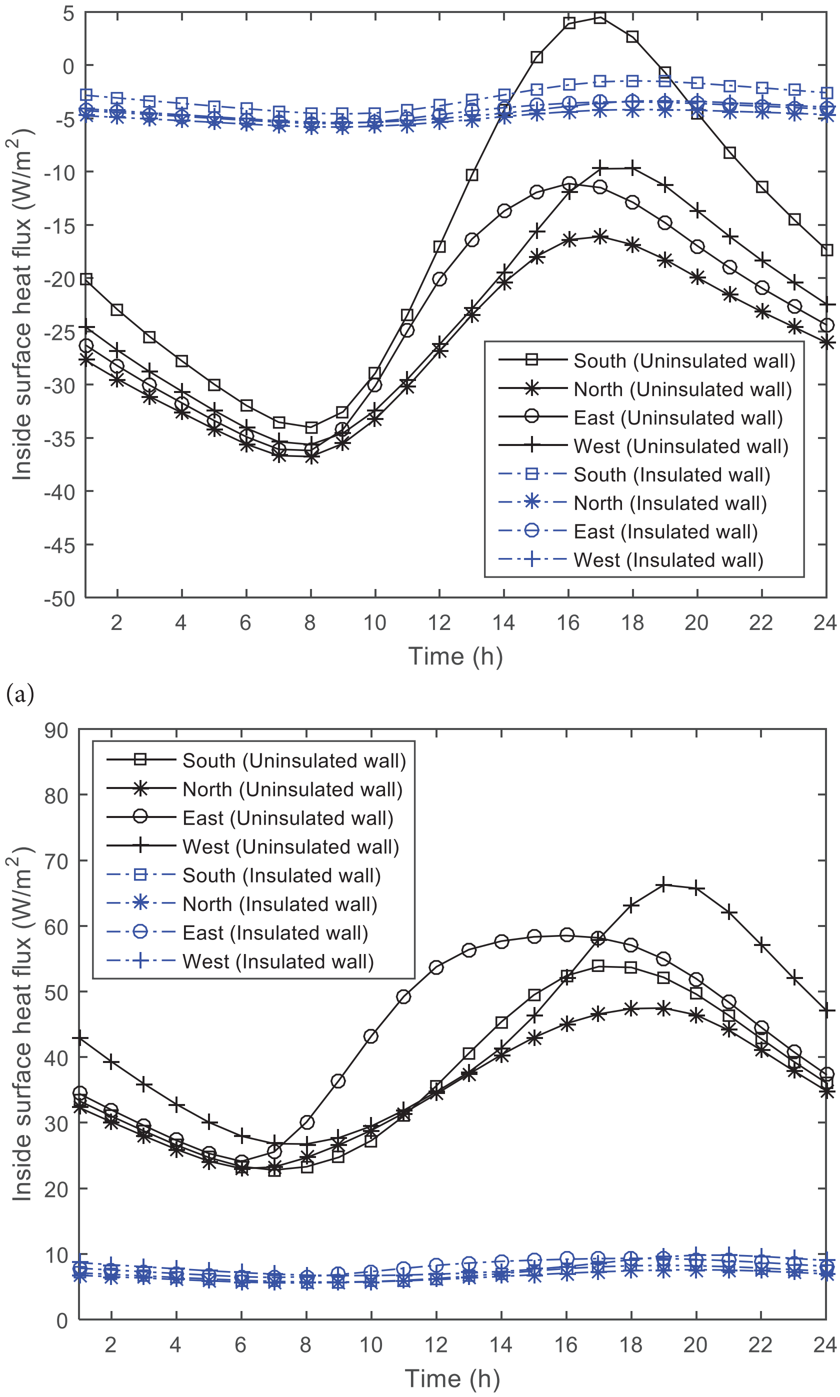
In this study, the wall structures are considered as uninsulated and insulated. The non-insulated wall consists of 2 cm thick outer plaster, 20 cm thick concrete block and 2 cm thick inner plaster. Also, the insulated wall comprises of 2 cm of outer plaster, 6 cm of insulation layer, 20 cm of concrete and 2 cm of interior plaster. The wall's solar absorptivity is

Table 1. Thermophysical properties of building materials

Material	k (W/m K)	ρ (kg/m³)	c (J/kg K)
Concrete	1.731	2243	840
RW	0.042	30	837
Cement plaster	0.720	1865	840

selected to be 0.8 for dark-colored surfaces [39]. Thermophysical characteristics of materials employed in the wall construction are shown in Table 1.

Figure 8(a-b) shows the change of internal surface heat flow through non-insulated and insulated walls for summer and winter conditions, respectively, in Antalya.

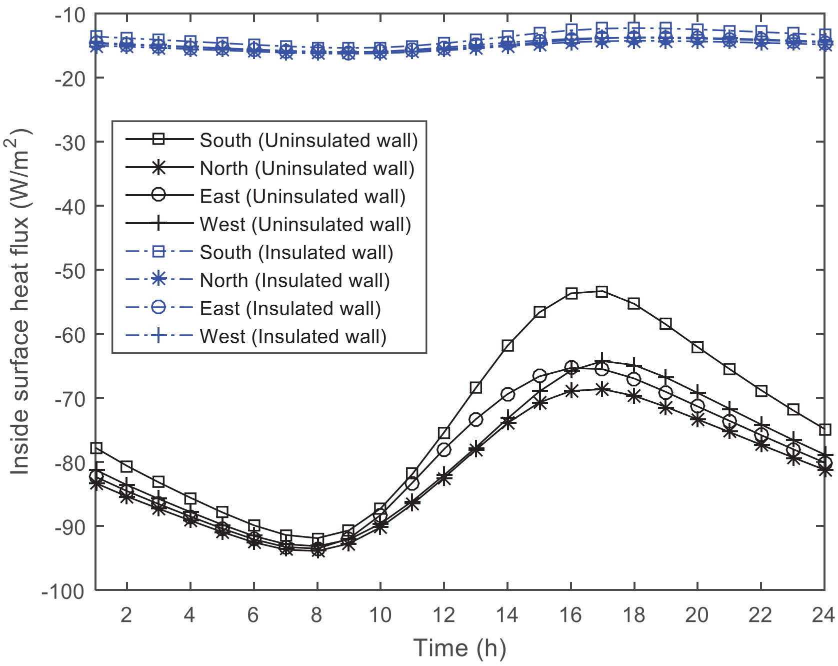


(a)

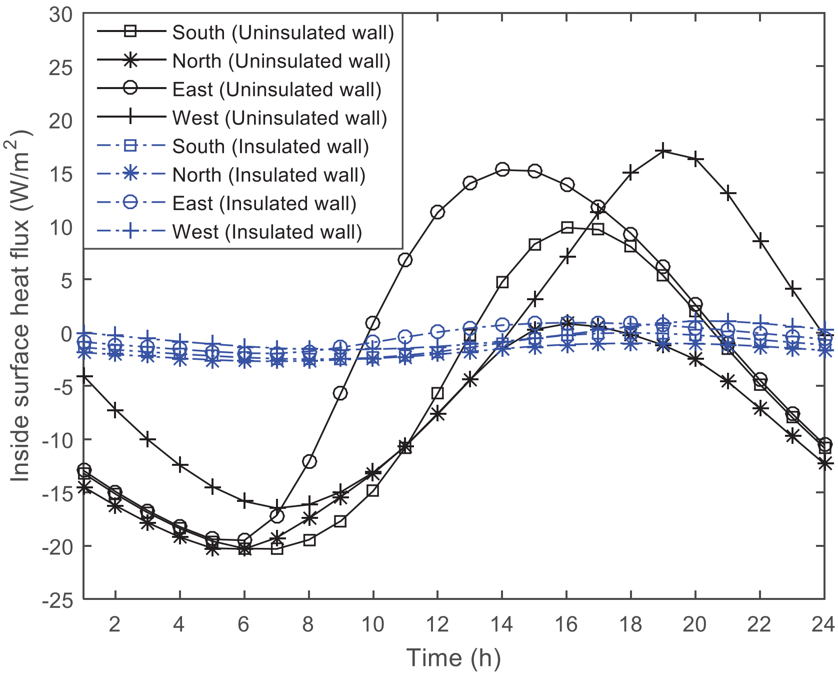
(b)

Figure 8. Variation of inside surface heat flux through uninsulated and insulated walls for a) winter and b) summer conditions in Antalya.

The variations of heat flux in Kars, Istanbul and Izmir are also indicated in Figure 9(a-b), Figure 10(a-b) and Figure 11(a-b), respectively. For the uninsulated wall in Antalya, it is revealed that in winter, maximum peak values of heat flux through the wall are obtained to be -34.00, -36.77, -36.19 and -35.63 W/m² for S, N, E and W orientations, respectively while in summer, it is obtained to be 53.80, 47.38, 58.52 and 66.24 W/m². For the uninsulated wall in Kars city, the maximum peak value of heat flux through the wall is obtained to be -91.89, -93.89, -93.51 and -93.15 W/m² for S, N, E and W orientations, respectively in the winter. On the other hand, it is obtained to be 9.85, 0.83, 15.27 and 17.02 W/m² in the summer. For the uninsulated wall in Istanbul, it is indicated that in the winter,



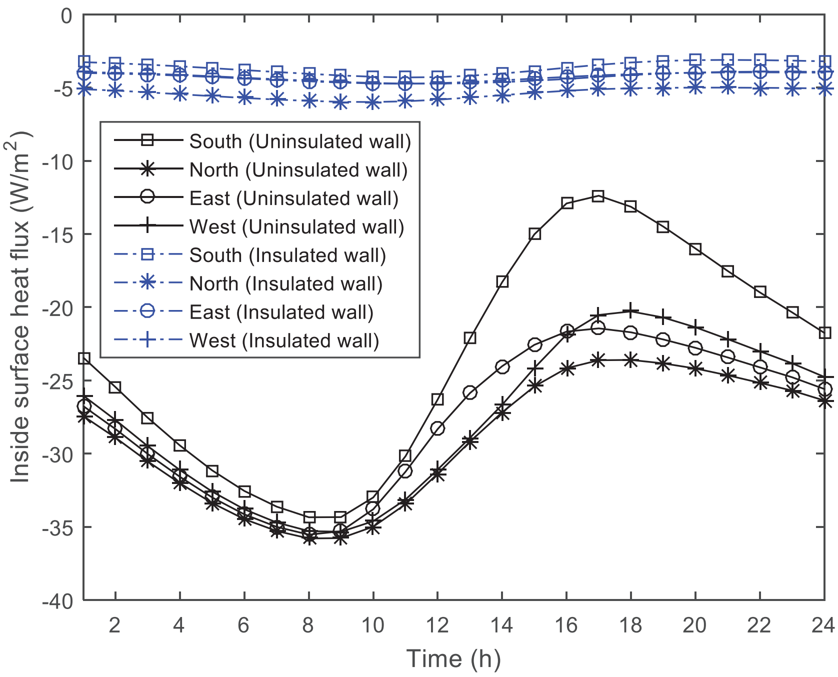
(a)



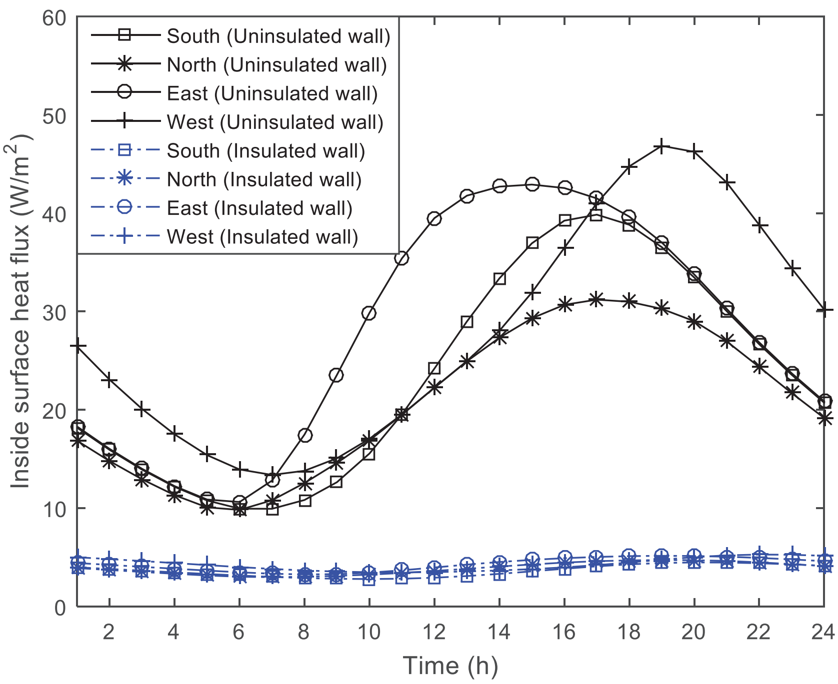
(b)

Figure 9. Variation of inside surface heat flux through uninsulated and insulated walls for a) winter and b) summer conditions in Kars.

the maximum peak value of heat flux through the wall is acquired to be -34.35, -35.80, -35.54 and -35.34 W/m^2 for S, N, E and W orientations, respectively. On the other hand, it is acquired to be 39.85, 31.20, 42.91 and 46.84 W/m^2 in the summer. For the uninsulated wall in Izmir, it is observed that in the winter, the maximum peak value of heat flux through the wall is obtained to be -28.07, -30.45, -29.95and -29.65 W/m^2 for S, N, E and W orientations, respectively. On the other hand, it is obtained to be 45.85, 39.24, 49.55 and 58.35 W/m^2 in the summer. The results indicate that in winter, the highest peak value of heat loss occurs in the N facade wall while the lowest peak value



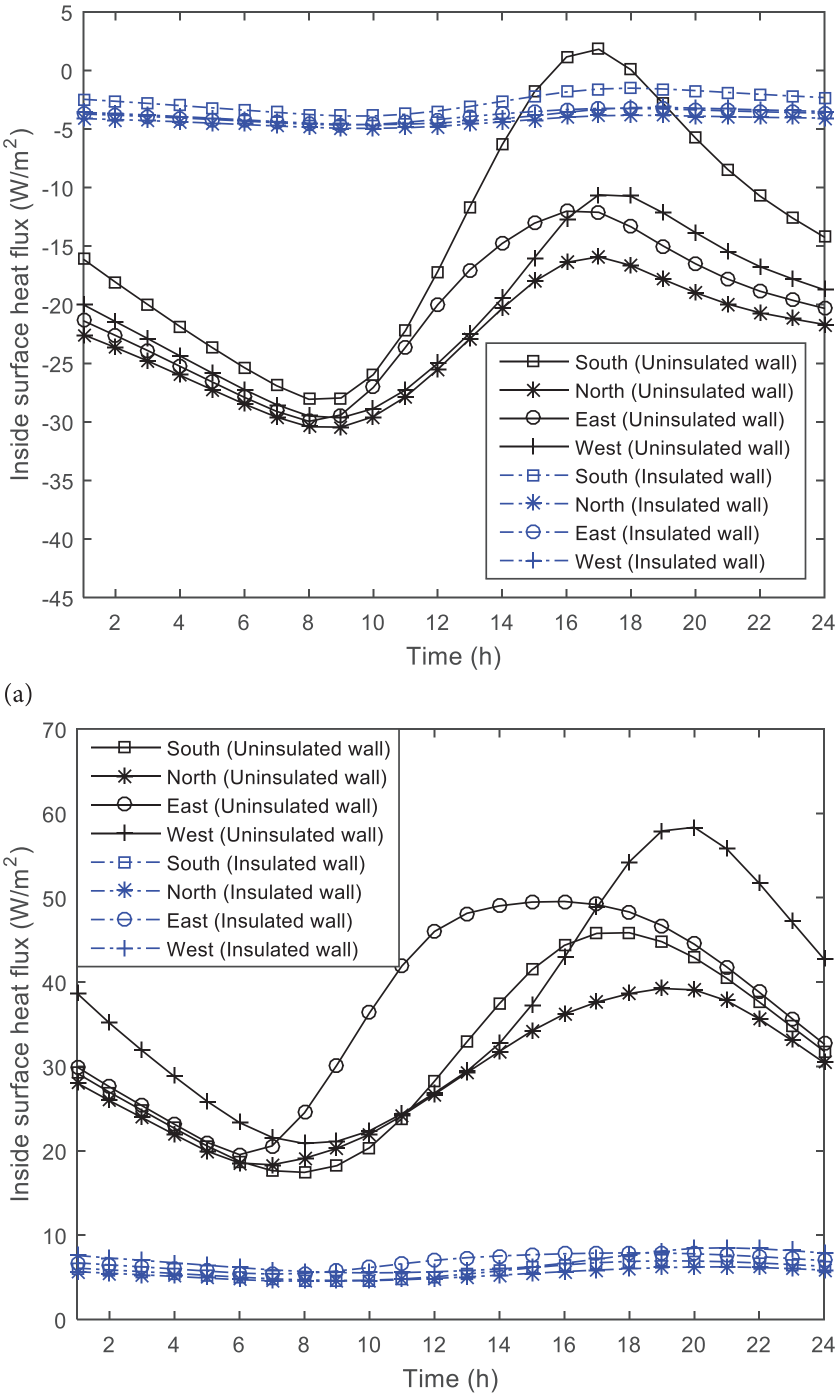
(a)



(b)

Figure 10. Variation of inside surface heat flux through uninsulated and insulated walls for a) winter and b) summer conditions in Istanbul.

of heat loss occurs in the S facade wall for all examined cities. On the one hand, it is observed that in the summer, the highest peak value of heat gain occurs in the W facade wall while the lowest peak value of heat gain occurs in the north-facing wall. It is seen that this case is connected with the peak value of the sol-air temperature. It is revealed that this result is in good agreement with those reported under the environmental conditions of Elazig, Türkiye [40]. Also, the results show that maximum heat loss is obtained in Kars while maximum heat gain is obtained in Antalya. It is seen that peak loads are considerably reduced if the wall is insulated. The results show that depending on the examined provinces, this reduction in winter varies among 83.27%-87.48% for S orientation,



(a)

(b)

Figure 11. Variation of inside surface heat flux through uninsulated and insulated walls for a) winter and b) summer conditions in Izmir.

82.67%-84.19% for N orientation, 82.96%-86.66% for E orientation and 82.88%-86.60% for W orientation. It is revealed that the best thermal performance occurs on the S façade wall while the worst thermal performance occurs on façadefacade wall for all examined cities. Same trends and similar results were achieved by references [6, 23] for different climates. In addition, it is revealed that in uninsulated wall, the orientations have an essential effect on heat gain and losses while this effect decreases in insulated wall.

Heat Transmission Loads Through Window

This study considers windows made of either single or double glass, with a glass thickness of 3mm for both. The window's thickness is quite small compared to its width and height. For this reason, window width and height are not taken into account, and solutions are made on a per-square-meter basis. The enclosed air space between the glass layers is 6mm thick, with a heat-transfer coefficient of 5.56 W/m2K. In calculations, Fs was taken to be 1. Clear plate glass was assumed, with a refractive index (n) of 1.526 and an extinction coefficient (K) of 6.85 m^{-1} [44]. For almost all types of window glass, the refractive index may be taken as 1.526 [44]. The τ, ρ, and α values of both single glass and double glass were computed by employing the characteristics of the glass mentioned above [40].

Figure 12(a-b) shows the variation of interior surface heat flux through single-glazed and double-glazed windows for summer and winter conditions, respectively, in Antalya. The variations of heat flux through windows in Kars, Istanbul and Izmir are also shown in Figure 13(a-b), Figure 14(a-b) and Figure 15(a-b), respectively. For Antalya city in winter conditions, it is observed that the maximum peak value of heat flux through the window is obtained to be 329.69, 36.26, 184.86 and 179.11W/m^2 for S, N, E and W orientations, respectively, in single glazing. On the other hand, it is acquired to be 294.12, 33.25, 174.25 and 171.57 W/m^2 in double glazing. In summer, it is observed that the maximum peak value of heat flux through the window is obtained to be 320.50, 175.94, 516.81 and 536.61 W/m^2 for S, N, E and W orientations, respectively, in single glazing. On the other hand, it is acquired to be 235.71, 122.23, 424.98 and 434.20 W/m^2 in double glazing. The conclusions indicate that in both winter and summer, double glazing reduces heat gain for all orientations. This reduction in summer is 26.45%, 30.53%, 17.77% and 19.08% while this reduction in winter is 10.79%, 8.30%, 5.74% and 4.21% for S, N, E and W orientations, respectively. It is observed that this decrease is more in the summer.

For Kars city in winter conditions, it is observed that the maximum peak value of heat flux through the window is acquired to be 163.92, -63.78, 25.92 and 17.61 W/m^2 for S, N, E and W orientations, respectively, in single glazing. On the other hand, it is acquired to be 187.25, -15.11, 71.94 and 68.08 W/m^2 in double glazing. In winter, it is observed that double glazing increases the heat gain in the S, E and W directions compared to single glazing, and decreases the heat loss in the N direction. In summer, it is observed that the maximum peak value of heat flux through the window is acquired to be 258.08, 88.48, 414.02 and 404.45 W/m^2 for S, N, E and W directions, respectively for single glazing. On the other hand, it is acquired to be 217.08, 66, 371.46 and 367.03 W/m^2 for double glazing. The results show that in summer, double glazing reduces heat gain for all orientations. This reduction is 15.66%, 25.41%, 10.27% and 9.25% for S, N, E and W directions, respectively.

For Istanbul city in winter conditions, it is observed that the maximum peak value of heat flux through the window is acquired to be 170.23, 2.07, 72.27 and 78.66 W/m^2 for S, N, E and W orientations, respectively, in single glazing. On the other hand, it is acquired to be 166.04, 14.23, 80.55 and 83.53 W/m^2 in double glazing. In winter, it is observed that for south orientation, double glazing reduces heat gain while for N, E and W directions, it increases heat gain. In summer, it is observed that the maximum peak value of heat flux through the window is obtained to be 300.25, 141.64, 445.81 and 440.05 W/m^2 for S, N, E and W orientations, respectively for single glazing. On the other hand, it is acquired to be 232.53, 91.57, 371.93 and 369.26 W/m^2 for double glazing. The results show that in summer, double glazing reduces heat gain for all orientations. This reduction is 22.55%, 35.35%, 16.57% and 16.01% for S, N, E and W directions, respectively.

For Izmir city in winter conditions, it is observed that the maximum peak value of heat flux through the window is acquired as 283.21, 25.97, 138.78 and 150.69 W/m^2 for S, N, E and W orientations, respectively, in single glazing. On the other hand, it is acquired as 256.37, 27.76, 138.32 and 144.56 W/m^2 in double glazing. In winter, it is observed that for S, E and W orientations, double glazing reduces heat gain while for north orientation, it increases heat gain. For Izmir city in summer, it is observed that the maximum peak value of heat flux through the window is obtained to be 306.31, 162.97, 490.39 and 517.85 W/m^2 for S, N, E and W orientations respectively, in single glazing. On the other hand, it is obtained to be 234.32, 120.37, 411.51 and 424.29 W/m^2, in double glazing. The results show that in summer, double glazing reduces heat gain for all directions. This reduction is 23.5%, 26.14%, 16.08% and 18.07% for S, N, E and W directions, respectively.

The results indicate that in summer, double glazing reduces heat gain for all orientations and all examined cities. The fact that the windows are double-glazed in Antalya reduces heat gain in summer more than in other examined provinces. In addition, it is seen that this decrease is highest in the north-facing window. It is revealed that in summer, the best thermal performance from double glazing point of view is obtained on the north orientation for all examined cities. In winter, it has been revealed that double glazing increases heat gain in all orientations in Kars, where the heating load is dominant, and reduces heat gain in Antalya, where the cooling load is dominant.

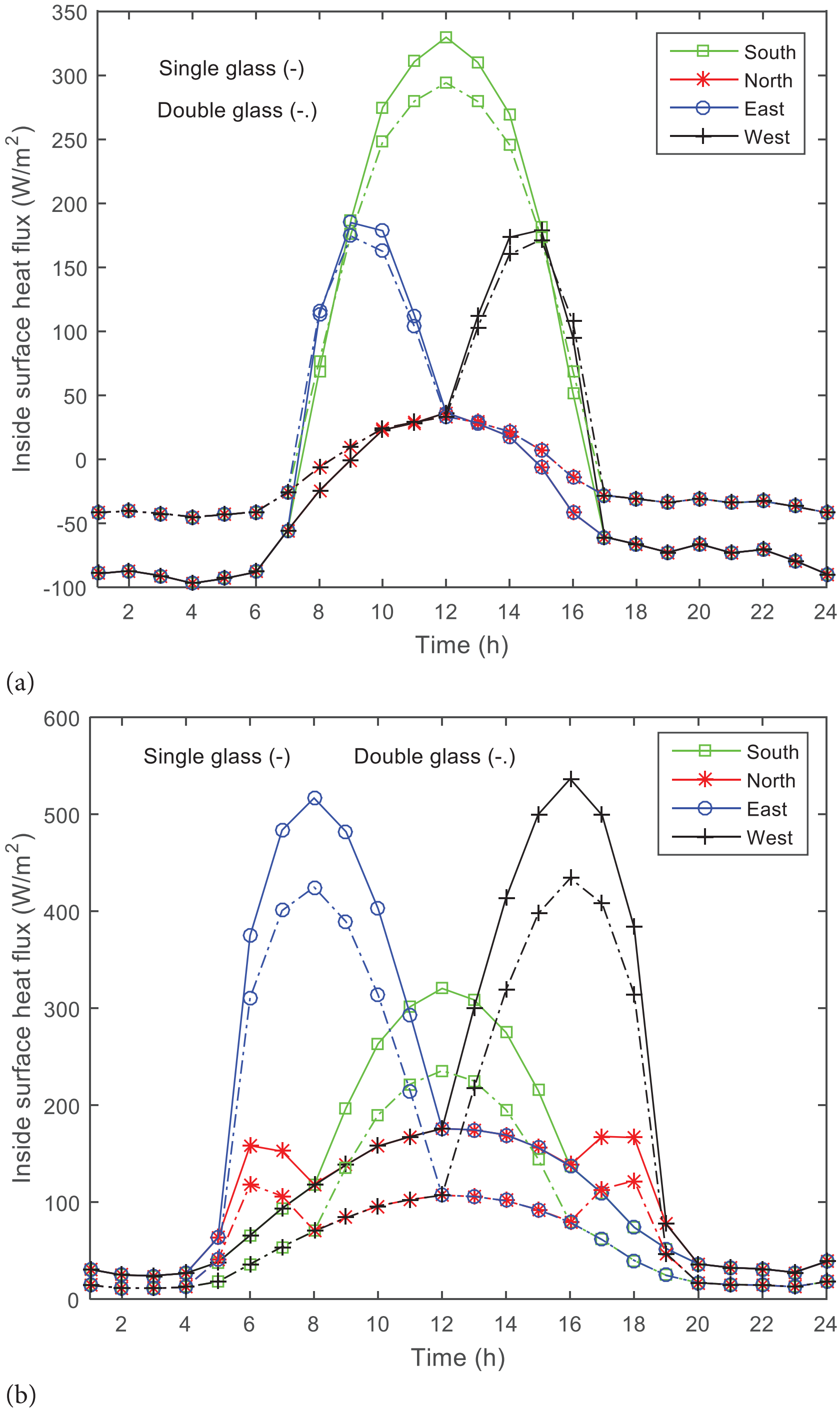


Figure 12. Variation of inside surface heat flux through single and double-glazed windows for a) winter and b) summer conditions in Antalya.

Glazing Area

Figure 16(a-b) shows the change of the transmission loads up against increasing glass area in insulated wall with different orientations in the summer and winter climates for the single glazing and double glazing, respectively, in Antalya. The similar variations for Kars, Istanbul and Izmir are also indicated in Figure 17(a-b), Figure 18(a-b) and Figure 19(a-b), respectively.

In Antalya, as the glazing area rises from 0% to 100%, the heat gain in summer rises for all orientations and each two glazing types. In summer, double glazing decreases heat gain by comparison to single glazing for all orientations. When the glass area is 100%, it is observed that

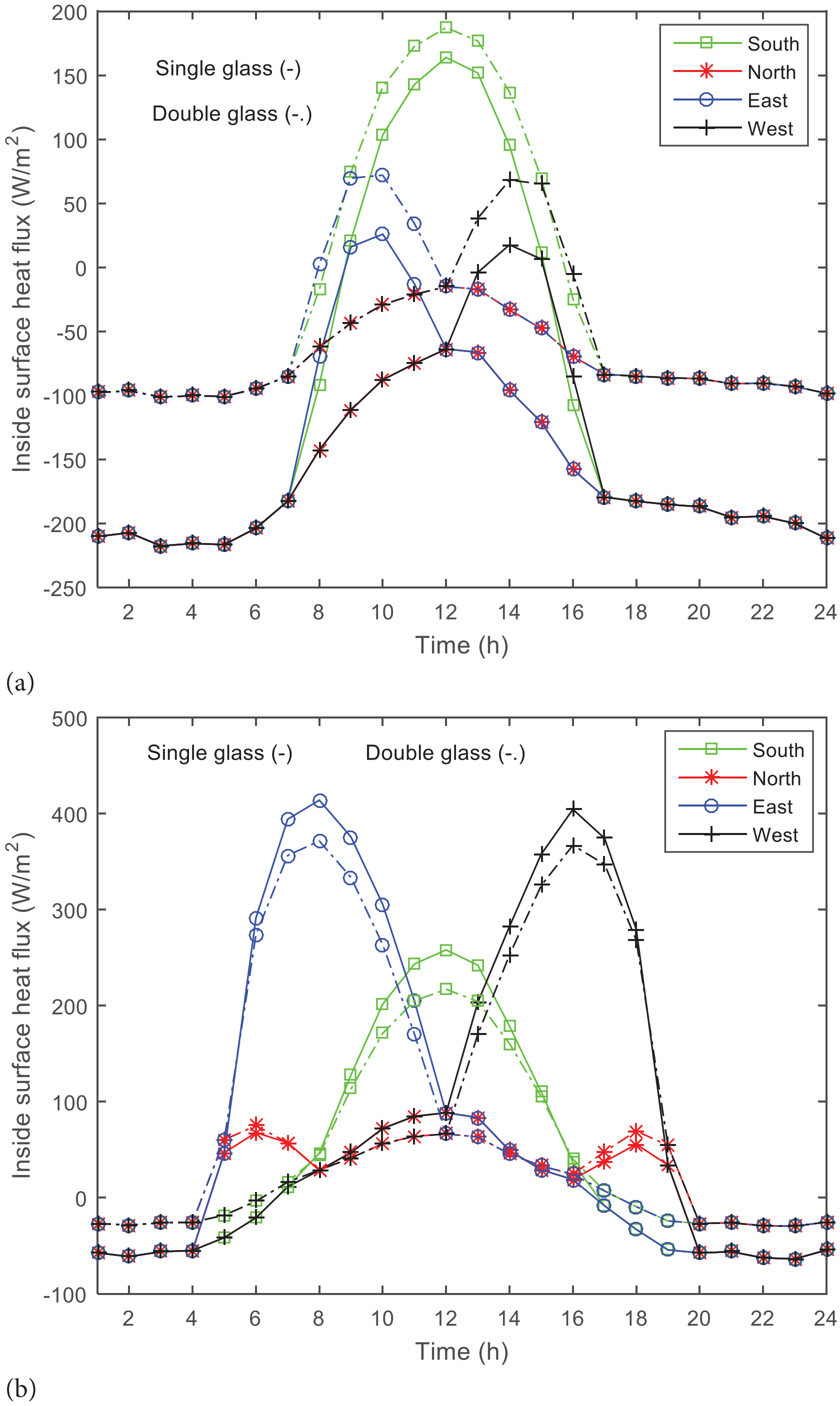
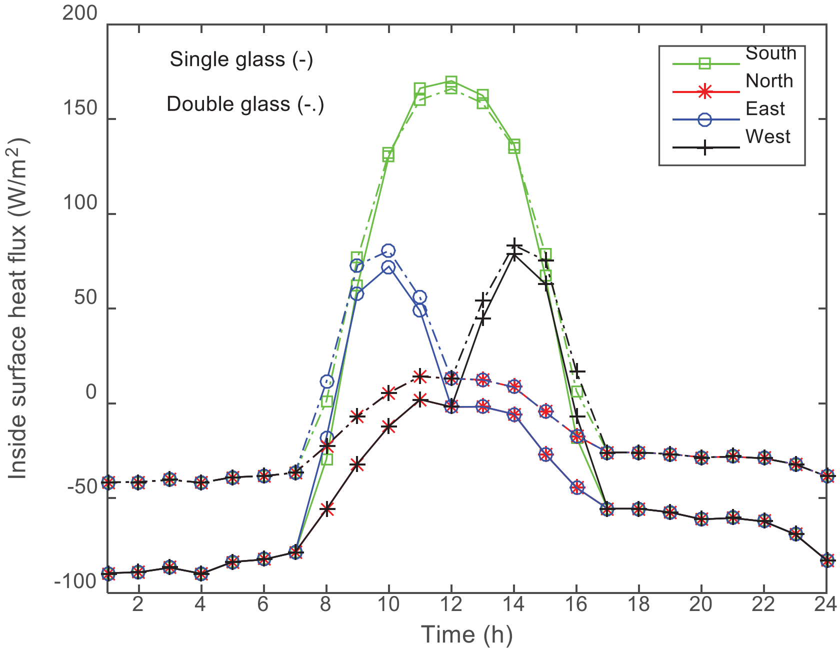
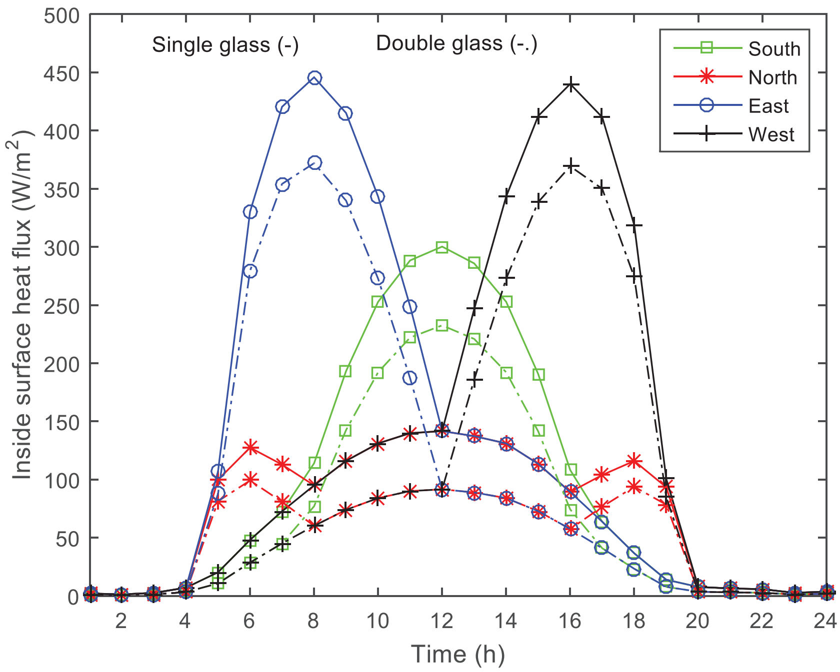


Figure 13. Variation of inside surface heat flux through single and double-glazed windows for a) winter and b) summer conditions in Kars.

double glazing decreases the heat gain compared to single glazing by 34.59%, 38.27% and 28% for S, N and E (or W) orientations, respectively. In the S facade wall in winter, for both single glass and double glass, heat loss occurs when the glazing area is 0%. At 10% of the glazing area, the heat gain begins and increases as far as 100%. It is revealed that double glazing increases in ratio 60.85% heat gain according to single glazing when the glazing area is 100%. In E and W orientations, the heat loss in winter increases for single glass as the glazing area increases from 0% to 100% while it decreases for double glass as the glazing area increases from 0% to 50%. In a double-glazed E (or W) facade wall, at 60% of the glazing area, the heat gain begins and increases as far as 100%. In the N facade wall, for both single glass and double glass, as the glazing area increases from 0% to 100%, the



(a)

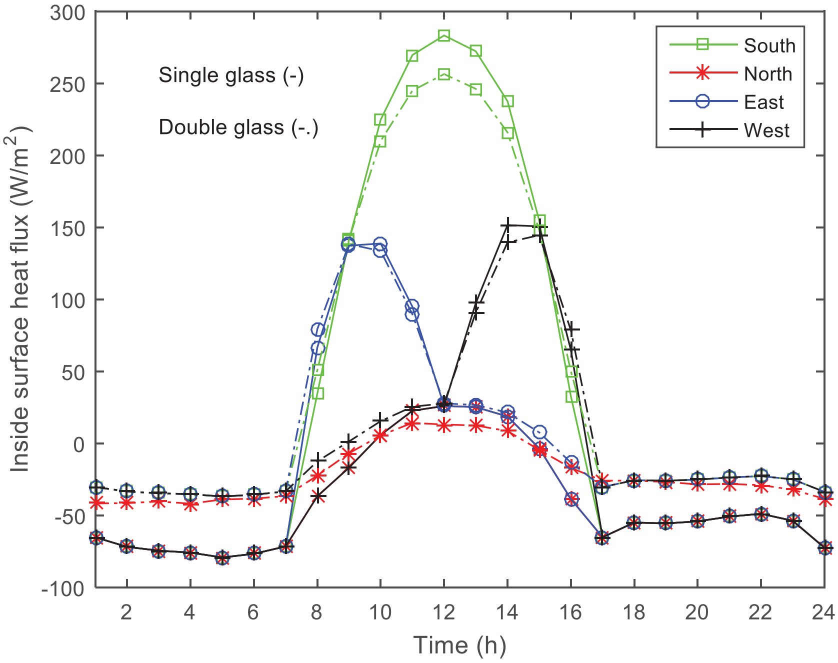


(b)

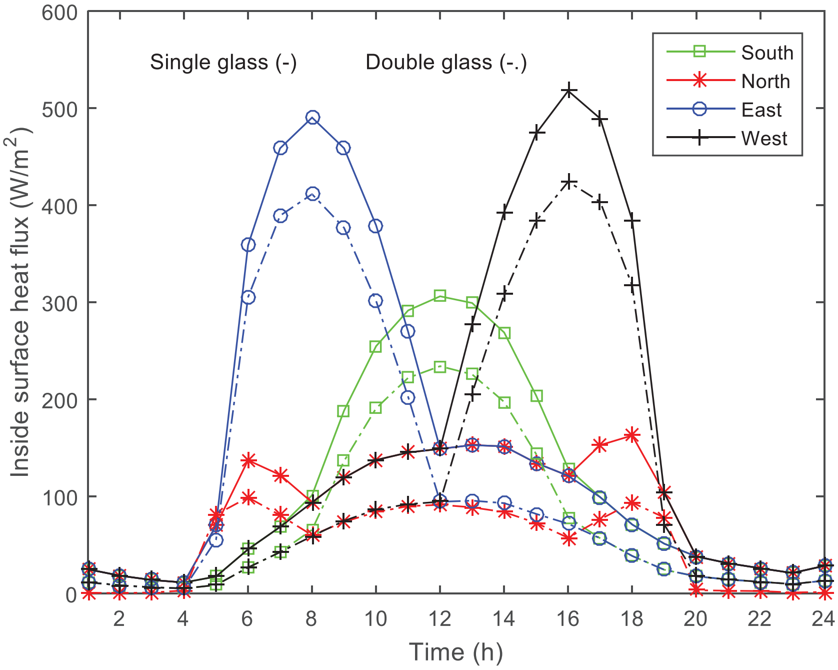
Figure 14. Variation of inside surface heat flux through single and double-glazed windows for a) winter and b) summer conditions in Istanbul.

heat loss in winter increases. It is revealed that this increase in double glazing is less than that in single glazing.

In summer in Kars, heat loss occurs for all orientations and for both single glass and double glass when the glazing area is 0%. At 10% of the glazing area, the heat gain begins and increases as far as 100%. It is observed that the use of double glazing in the windows in summer compared to single glazing increases the heat gain for all orientations. When the glass area is 100%, the double glazing raises the heat gain compared to single glazing by 27.33%, 96.48% and 6.58% for S, N and E (or W) orientations, respectively. In winter in Kars, as the glazing area rises from 0% to 100%, the heat loss rises for whole orientations and each two glazing types. It is observed that as expected, double glazing in winter reduces heat loss for all orientations. When the glass area is 100%, double glazing decreases the heat loss



(a)

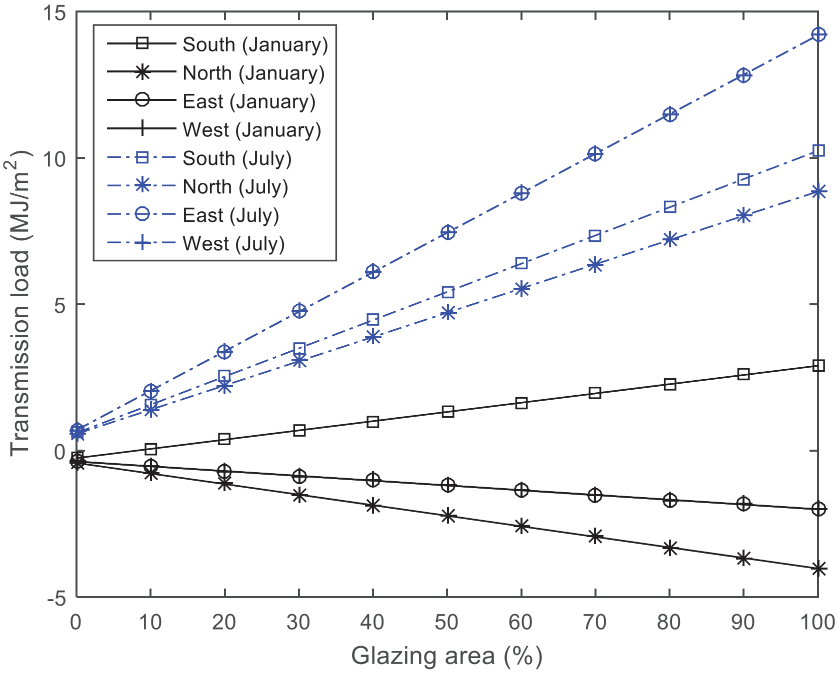


(b)

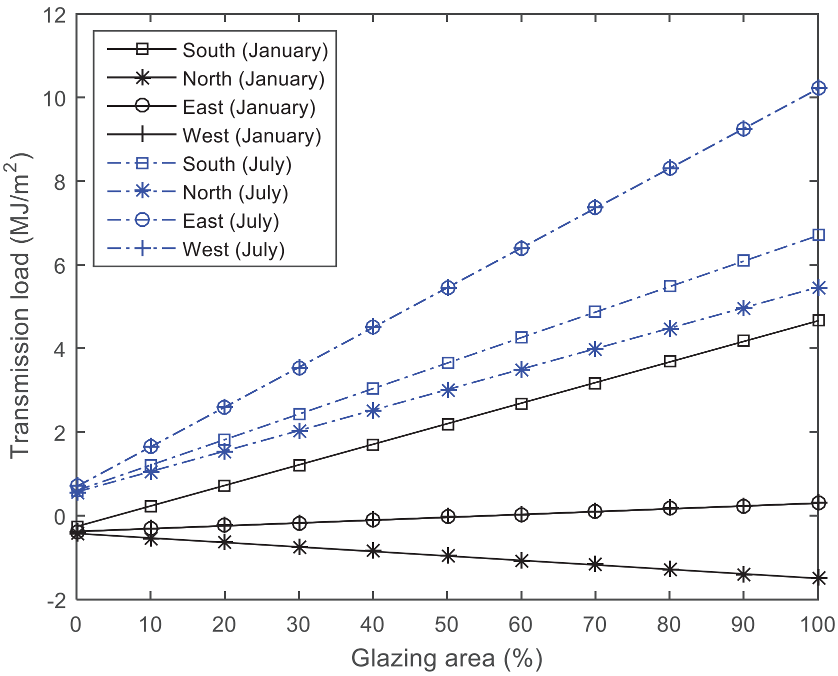
Figure 15. Variation of inside surface heat flux through single and double-glazed windows for a) winter and b) summer conditions in Izmir.

compared to single glazing by 81%, 55.77% and 60.53% for S, N and E (or W) orientations, respectively.

In Istanbul, as the glazing area rises from 0 to 100%, the heat gain in summer rises for whole directions and for both glazing types. It is observed that in summer, double-glazed windows decrease the heat gain for all orientations. When the glass area is 100%, it is revealed that double glazing decreases the heat gain compared to single glazing by 26.77%, 21.09% and 22.72% for S, N and E (or W) orientations, respectively. In winter in Istanbul, as the glazing area rises from 0 to 100%, the heat loss in single glazing rises for all orientations while the heat loss in double glazing increases for N, E and W orientations. It is observed that in winter, the double glazing reduces the heat loss for N, E



(a)



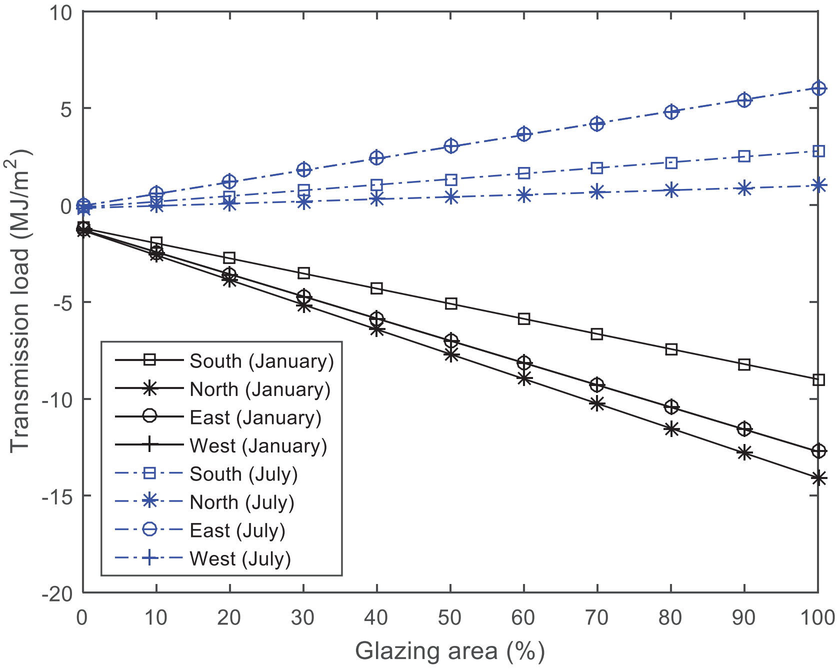
(b)

Figure 16. Variation of the transmission loads according to increasing glazing area in the insulated wall with different orientations in summer and winter conditions for a) single and b) double glazing in Antalya.

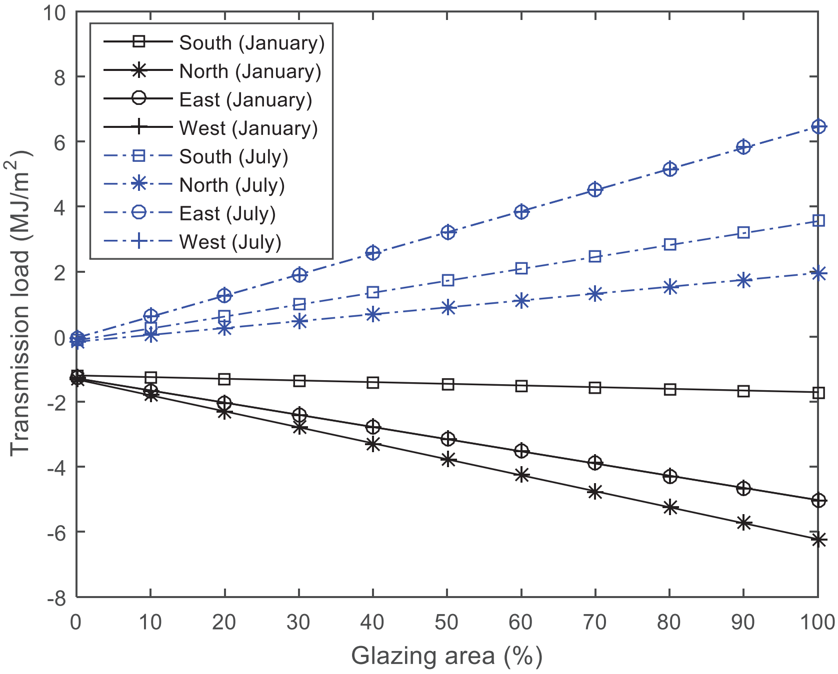
and W orientations. When the glass area is 100%, double glazing reduces heat loss by 60.20% and 72.60% in the N and E (or W) orientations, respectively, compared to single glazing. In the double-glazed south wall in winter, as the glazing area rises from 0% to 10%, heat loss decreases. At 20% of the glazing area, the heat gain begins and rises as far as 100%.

In Izmir, as the glazing area rises from 0% to 100%, the heat gain in summer rises for whole orientations and for both glazing types. However, it is observed that in summer, double-glazed windows decrease the heat gain for all orientations. When the glass area is 100%, it is revealed that double glazing reduces the heat gain compared to single glazing by 31.3%, 35.43% and 25.65% for S, N and E (or

J Ther Eng, Vol. 11, No. 2, pp. 519−549, March, 2025



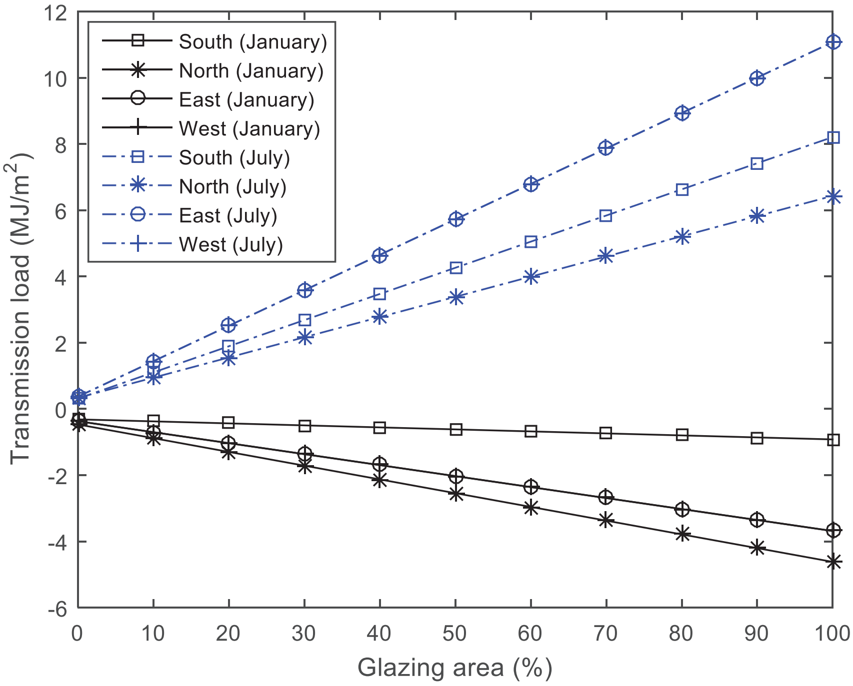
(a)



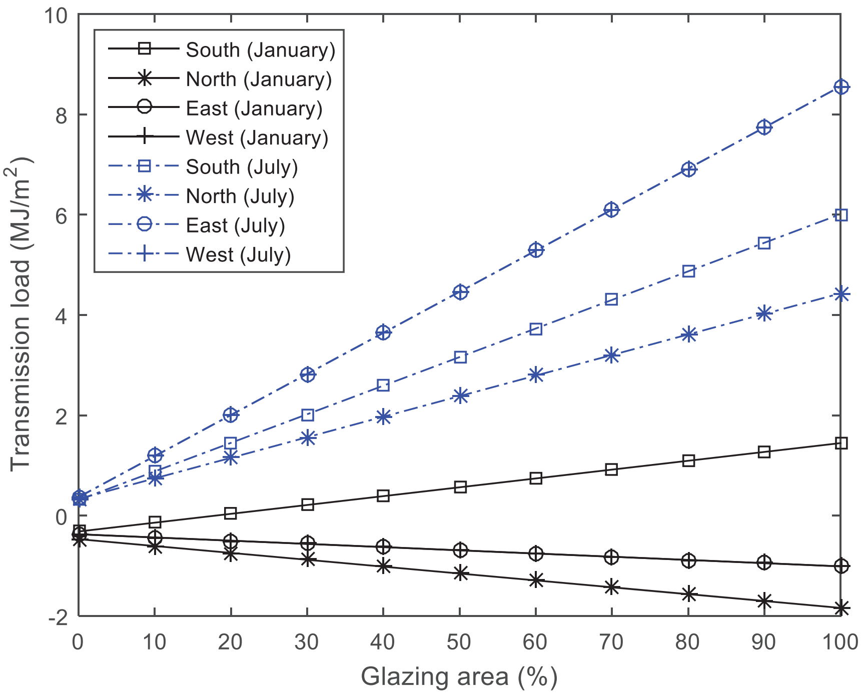
(b)

Figure 17. Variation of the transmission loads according to increasing glazing area in the insulated wall with different orientations in summer and winter conditions for a) single and b) double glazing in Kars.

W) orientations, respectively. In winter, in the north-facing wall, heat loss increases for single and double glazing as the glazing area increases from 0% to 100%. But, the double glazing of windows by comparison to single glazing reduces the heat loss for north orientation. When the glass area is 100%, this reduction is 63.66%. In E (or W)-facing wall, heat loss increases for single glazing while it decreases up to 60% of the glazing area for double glazing. But, after 60% of the glazing area, the heat gain begins and increases as far as 100%. In the south-facing wall, in winter heat loss occurs for each two glazing types when the glazing area is 0%. At 10% of the glazing area, the heat gain begins and increases as far as 100%.



(a)



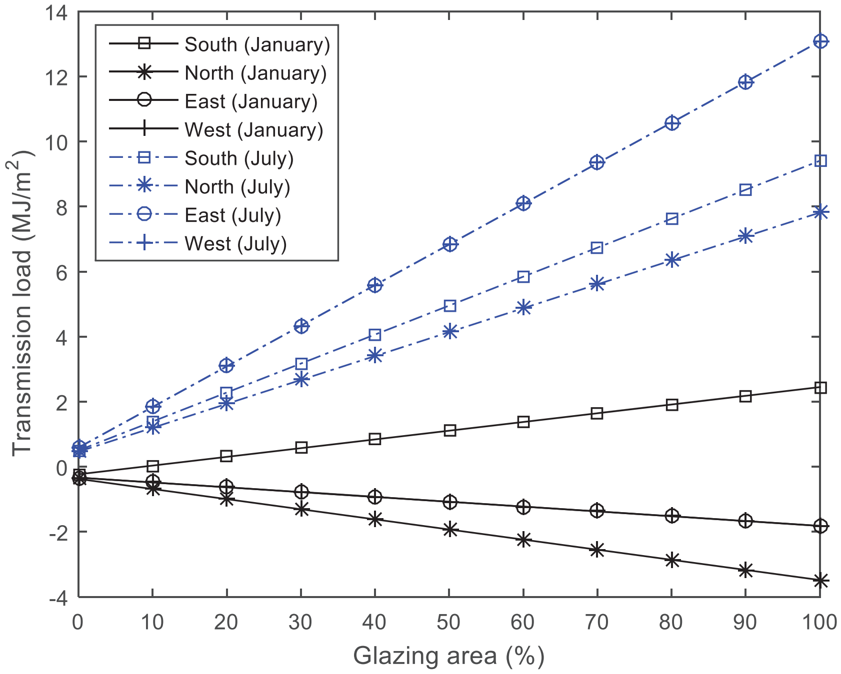
(b)

Figure 18. Variation of the transmission loads according to increasing glazing area in the insulated wall with different orientations in summer and winter conditions for a) single and b) double glazing in Istanbul.

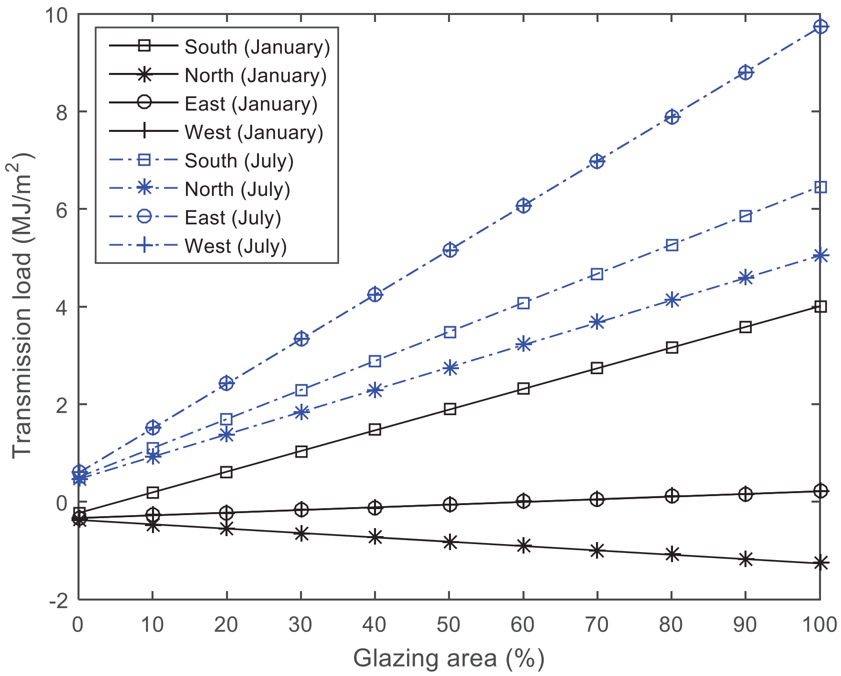
As a result, it is seen that the increment in the glazing area induces an additional heating and cooling load for whole wall orientations and examined cities. This conclusion is in accord with the conclusions of other works reported under different climate conditions [27, 40, 41]. It is revealed that this increase in heating and cooling load is reduced by double glazing.

Energy Requirements and Costs

Figure 20(a-b) shows the variation of the heating and cooling energy requirements according to examined cities



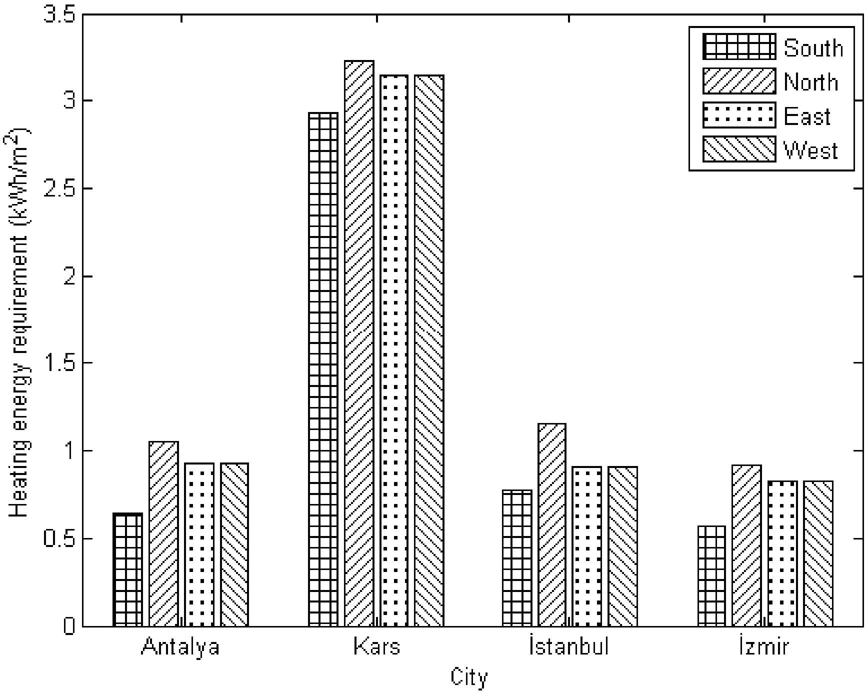
(a)



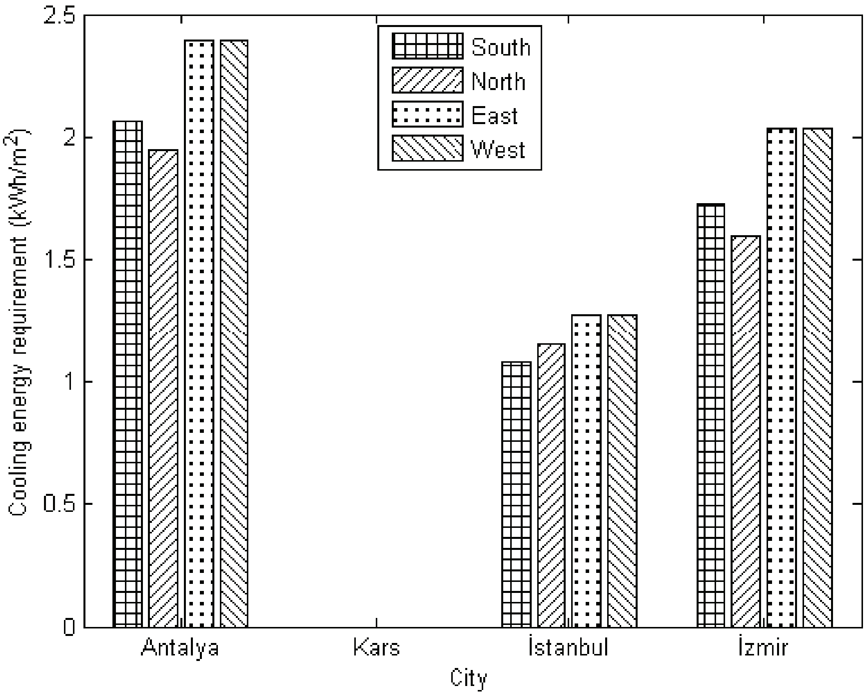
(b)

Figure 19. Variation of the transmission loads according to increasing glazing area in the insulated wall with different orientations in summer and winter conditions for a) single and b) double glazing in Izmir.

by considering orientations for an insulated wall without the window. Figure 21(a-b) shows variations of the heating and cooling energy requirements according to examined cities for different orientations by applying a window with single glazing of 40% on an insulated wall. A similar variation is shown for double glazing Figure 22(a-b). Energy costs for heating and cooling are also shown in Figure 23(a-b). These energy requirements and costs represent the values of a month for January and July months. It is seen that for all orientations, there is no need for cooling energy on 6 cm insulated wall without the window in Kars city. In the S direction, it is also seen that there is no need



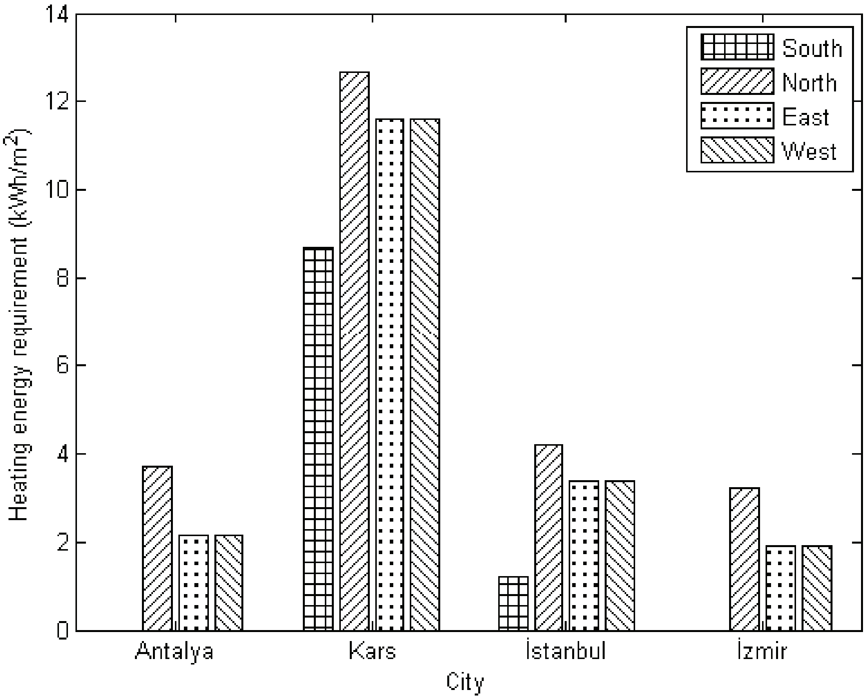
(a)



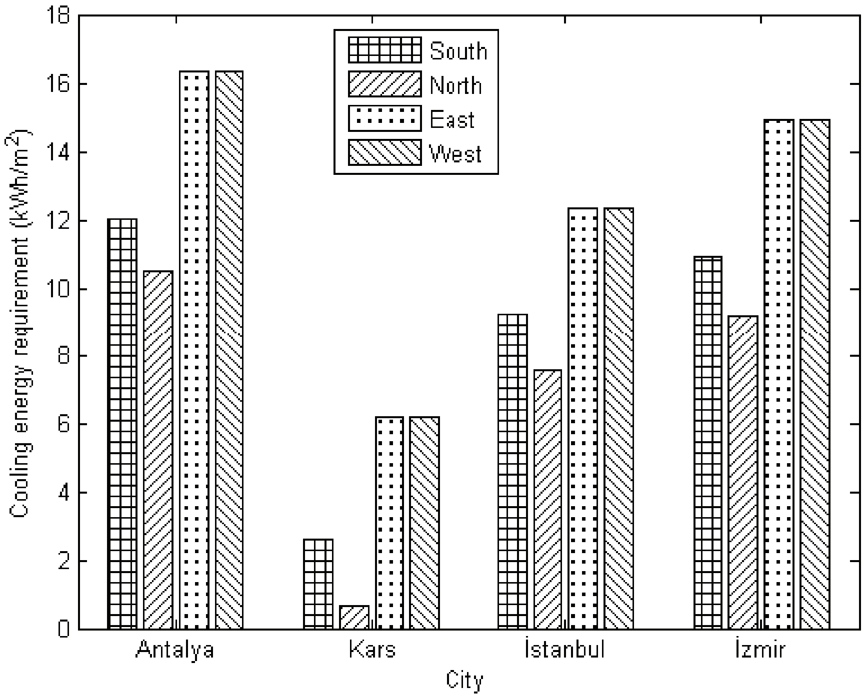
(b)

Figure 20. Variation of the heating and cooling energy requirements according to examined cities by considering orientations for an insulated wall without window.

for heating energy in Antalya and Izmir provinces for single glazing and in Antalya, Istanbul, and Izmir provinces for double glazing. The results indicate that the highest heating energy requirement and cost are obtained in Kars which is one of the coldest provinces of Türkiye while the highest cooling energy requirement and cost are obtained in Antalya which is one of the hottest provinces of Türkiye. These energy needs and costs can be reduced by applying



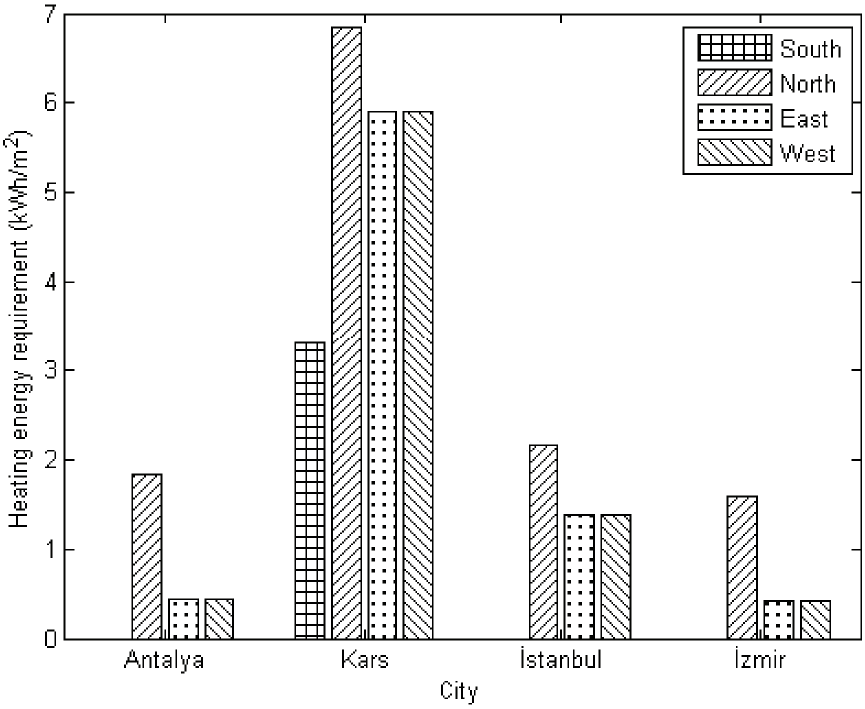
(a)



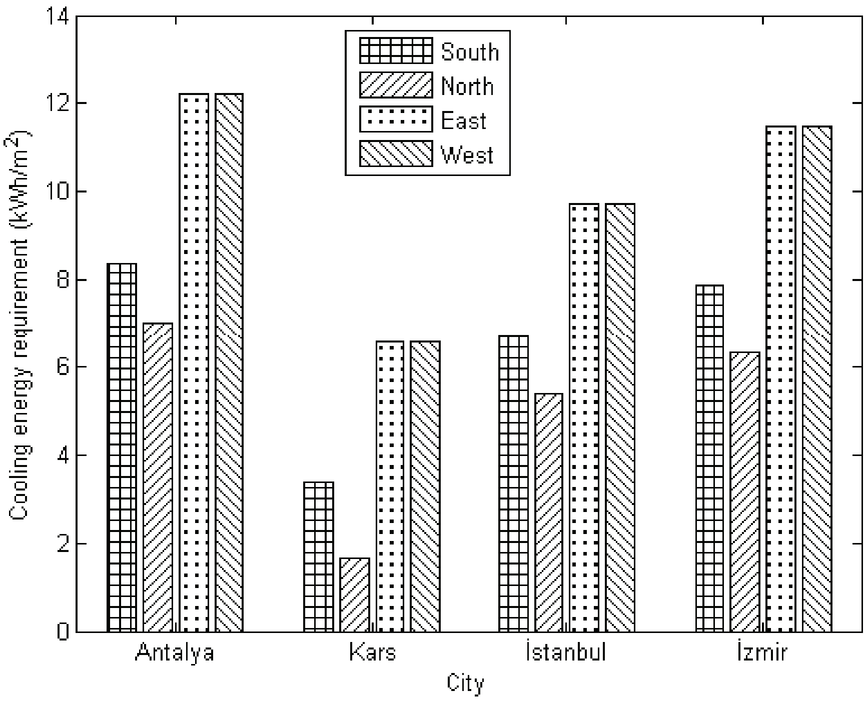
(b)

Figure 21. Variation of the heating and cooling energy requirements according to examined cities by considering orientations for single glass by using glazing of 40% on insulated wall.

double glazing instead of single glazing on the wall. In Kars city, it is indicated that for single glazing, the heating requirement is obtained to be 8.69, 12.66, 11.60 and 11.60 kWh/m^2 for S, N, E and W orientations, respectively. On the other hand, it is obtained to be 3.31, 6.85, 5.91 and 5.91 kWh/m^2 for double glazing. In Antalya city, it is also indicated that for single glazing, the cooling requirement is obtained to be 12.02, 10.51, 16.33, 16.33 kWh/m^2 for S,



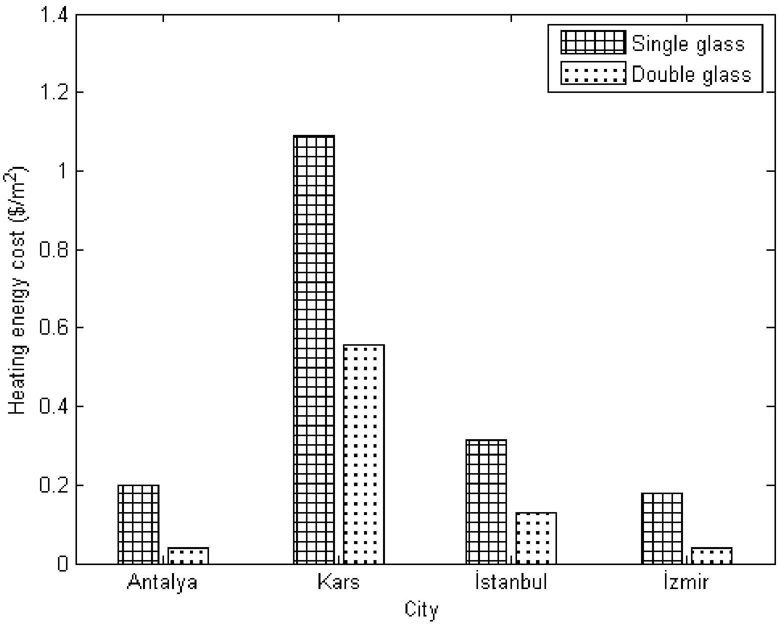
(a)



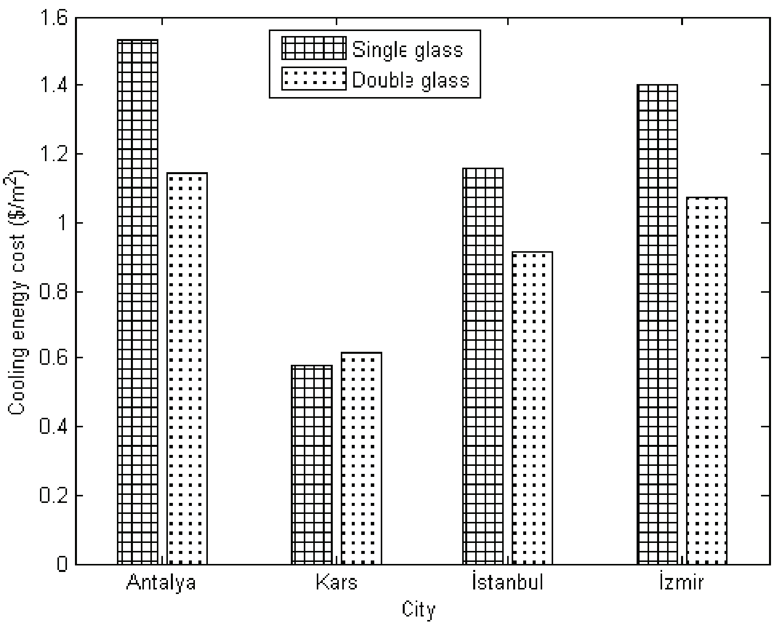
(b)

Figure 22. Variation of the heating and cooling energy requirements according to examined cities by considering orientations for double glass by using glazing of 40% on insulated wall.

N, E, W orientations, respectively. On the other hand, it is obtained to be 8.36, 7.01, 12.22, 12.22 kWh/m^2 for double glazing. The results show that this reduction in heating need for Kars is 61.91%, 45.81%, 49.01% and 49.01% for S, N, E and W orientations, respectively. On the other hand, it is seen that this decrease in cooling need for Antalya



(a)



(b)

Figure 23. Variation of the heating and cooling energy costs according to examined cities for west (or east) orientation by using glazing of 40% on insulated wall.

is 30.45%, 33.30%, 25.17% and 25.17%. It is observed that double glazing significantly reduces heating energy requirements for all orientations.

CONCLUSION

The goal of this study is to find the best design features that can make residential buildings energy efficient for the studied latitudes. For this purpose, in this work, the effects of wall, window and glazing area on thermal performance conditions and and energy requirements are numerically researched by considering wall orientations for four cities representing four climatic zones in Türkiye. It is revealed that for all orientations in winter, the difference in solar radiation among provinces is quite obvious, but in summer this difference becomes unimportant. The results show that in climates where cooling is dominant, such as Antalya, double glazing increases heat gain in winter and reduces it in summer. The results also show that double glazing significantly reduces heat loss during winter months in climates where heating is dominant, such as Kars. It is seen that the highest heating energy requirement and cost are obtained for the north orientation in Kars province while the highest cooling energy requirement and cost are obtained for the west (or east) orientation in Antalya province. It is observed that in winter, the highest energy saving is acquired in the south orientation while in summer, it is acquired in the north orientation. Also, the double glazing appears to be more effective at reducing heating demand than at reducing cooling demand. The results show that energy saving is significantly provided for air-conditioning by applying double glazing on the wall.

Consequently, it is observed that the orientation, climate conditions, geographical location, type of glazing, glazing area and insulation have a notable effect on heat transmission and energy requirement. With the appropriate combination of window glass area, glazing type and wall insulation, heating and cooling loads and therefore energy requirements can be significantly reduced. The results acquired in this work will be very beneficial in the selection of glass type and the glazing area, taking into account the wall direction, when designing exterior walls of residential buildings in different climatic zones.

The glazing area not only affects the heat gain and losses but it also affects the daylight factor. However, this study focuses on the thermal analysis of the wall and window components of the building under different climatic conditions and then, energy requirements. Therefore, the daylight factor isn't taken into consideration in this study. In addition, this study can be extended by considering together thermal and daylight factors. The effect of artificial lighting on energy consumption can also be investigated in another study.

NOMENCLATURE

a	absorption coefficient
A_g	glass area (m^2)
A_w	wall area (m^2)
c	specific heat (J/kg K)
Ce	cost of electricity ($/kWh)
COP_c	performance of the air-conditioning system for cooling
COP_h	performance of the air-conditioning system for heating
E_c	cooling energy requirement (kWh/m^2)
E_h	heating energy requirement (kWh/m^2)
F_s	sunlit fraction of the window surface
h_i	heat-transfer coefficient at the indoor surface of wall (W/m^2 K)
h_o	heat-transfer coefficient at the outdoor surface of wall (W/m^2 K)
I_D	incidence of direct radiation (W/m^2)
I_d	incidence of diffuse sky radiation (W/m^2)
I_R	incidence of solar radiation reflected (W/m^2)
I	total solar radiations on the horizontal surface (W/m^2)
k	thermal conductivity (W/m K)
K	extinction coefficient,(m^{-1})
L	glass thickness, (m)
L'	distance traveled by radiation, (m)
L_i	insulation thickness (m)
n	index of refraction for glass
q_{idg}	heat gain (or loss) ratio for a double-glazed window (W/m^2)
q_{isg}	heat gain (or loss) ratio for a single-glazed window (W/m^2)
q_{iw}	heat flux at indoor surface of the wall (W/m^2)
Q_{idg}	daily total load for a double-glazed window (MJ/m^2)
Q_{isg}	daily total load for a single-glazed window (MJ / m^2)
Q_{iw}	daily total load of the wall (MJ /m^2)
r	reflectivity
t	time (s)
T_i	indoor air temperature (^{o}C)
T_o	outdoor air temperature (^{o}C)

Greek symbols

α_o	solar absorptivity of outdoor surface of wall
α	absorptivity for a single sheet of glass
ρ_i	density (kg/m^3)
ρ	reflectivity for a single sheet of glass
θ	incidence angle (deg.)
θ_z	zenith angle (deg.)
θ'	refraction angle, (deg.)
θ_{ey}	incidence angle for diffuse sky radiation (deg.)
θ_{ya}	incidence angle for reflected radiation (deg.)
τ	transmissivity for a single sheet of glass

AUTHORSHIP CONTRIBUTIONS

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.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Zenginis DG, Kontoleon KJ. Influence of orientation, glazing proportion and zone aspect ratio on the thermal performance of buildings during the winter period. Environ Sci Pollut Res 2018;25:26736–26746. [CrossRef]

[2] Kontoleon KJ, Theodosiou TG, Tsikaloudaki KG. The influence of concrete density and conductivity on walls' thermal inertia parameters under a variety of masonry and insulation placements. Appl Energy 2013;112:325–337. [CrossRef]

[3] Kirankumar G, Saboor S, Ashok Babu TP. Thermal analysis of wall and window glass materials for cooling load reduction in green energy building design. Mater Today Proc 2017;4:9514–9518. [CrossRef]

[4] Kontoleon KJ. Dynamic thermal circuit modelling with distribution of internal solar radiation on varying faade orientations. Energy Build 2012;47:139–150. [CrossRef]

[5] Ghisi E, Tinker J. Optimising energy consumption in offices as a function of window area and room size. Seventh Int IBPSA Conf 2001:1307–1314.

[6] Al-Sanea SA. Thermal performance of building roof elements. Build Environ 2002;37:665–675. [CrossRef]

[7] Bojić ML, Loveday DL. The influence on building thermal behavior of the insulation/masonry distribution in a three-layered construction. Energy Build 1997;26:153–157. [CrossRef]

[8] Shaid M, Karimi MN, Mishra AK. Optimum insulation thickness for external building walls for different climate zone in India. J Therm Eng 2024;10:1198–1211. [CrossRef]

[9] Al-Sanea SA, Zedan MF. Effect of insulation location on thermal performance of building walls under steady periodic conditions. Int J Ambient Energy 2001;22:59–72. [CrossRef]

[10] Al-Sanea SA, Zedan MF. Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass. Appl Energy 2011;88:3113–3124. [CrossRef]

[11] Al-Sanea SA, Zedan MF. Optimized monthly-fixed thermostat-setting scheme for maximum energy-savings and thermal comfort in air-conditioned spaces. Appl Energy 2008;85:326–346. [CrossRef]

[12] Daouas N, Hassen Z, Ben AH. Analytical periodic solution for the study of thermal performance and optimum insulation thickness of building walls in Tunisia. Appl Therm Eng 2010;30:319–326. [CrossRef]

[13] Kaşka Ö, Yumrutaş R. Comparison of experimental and theoretical results for the transient heat flow through multilayer walls and flat roofs. Energy 2008;33:1816–1823. [CrossRef]

[14] Kaşka Ö, Yumrutaş R, Arpa O. Theoretical and experimental investigation of total equivalent temperature difference (TETD) values for building walls and flat roofs in Turkey. Appl Energy 2009;86:737–747. [CrossRef]

[15] Aguilar JO, Xamán J, Olazo-Gómez Y, Hernández-López I, Becerra G, Jaramillo OA. Thermal performance of a room with a double glazing window using glazing available in Mexican market. Appl Therm Eng 2017;119:505–515. [CrossRef]

[16] Saafi K, Daouas N. Energy and cost efficiency of phase change materials integrated in building envelopes under Tunisia Mediterranean climate. Energy 2019;187:115987. [CrossRef]

[17] Liu Z, Hou J, Wei D, Meng X, Dewancker BJ. Thermal performance analysis of lightweight building walls in different directions integrated with phase change materials (PCM). Case Stud Therm Eng 2022;40:102536. [CrossRef]

[18] Al-Absi ZA, Hafizal MIM, Ismail M. Experimental study on the thermal performance of PCM-based panels developed for exterior finishes of building walls. J Build Eng 2022;52:104379. [CrossRef]

[19] Cho K, Cho D, Koo B, Yun Y. Thermal performance analysis of windows, based on argon gas percentages between window glasses. Buildings 2023;13:2935. [CrossRef]

[20] Li Z, Si Y, Zhao Q, Feng X. A new method of building envelope thermal performance evaluation considering window–wall correlation. Energies 2023;16:16196927. [CrossRef]

[21] Tan YY, Awang H, Isa MHM. Thermal performance and energy efficiency of different types of walls for residential building. Int J Sustain Constr Eng Technol 2022;13:218–231. [CrossRef]

[22] Romdhane SB, Amamou A, Mahjoub H, Said NM, Jemni A, Younsi Z. Numerical study on thermal performance of a building design integrating two passive Trombe walls. Adv Build Energy Res 2023;17:679–709. [CrossRef]

[23] Ozel M. Thermal performance and optimum insulation thickness of building walls with different structure materials. Appl Therm Eng 2011;31:3854–3863. [CrossRef]

[24] Kontoleon KJ, Zenginis DG. Analysing heat flows through building zones in aspect of their orientation and glazing proportion, under varying conditions. Procedia Environ Sci 2017;38:348–355. [CrossRef]

[25] Kontoleon KJ, Bikas DK. Modeling the influence of glazed openings percentage and type of glazing on the thermal zone behavior. Energy Build 2002;34:389–399. [CrossRef]

[26] Jaber S, Ajib S. Thermal and economic windows design for different climate zones. Energy Build 2011;43:3208–3215. [CrossRef]

[27] Derradji L, Imessad K, Amara M, Boudali Errebai F. A study on residential energy requirement and the effect of the glazing on the optimum insulation thickness. Appl Therm Eng 2017;112:975–985. [CrossRef]

[28] Arici M, Karabay H. Determination of optimum thickness of double-glazed windows for the climatic regions of Turkey. Energy Build 2010;42:1773–1778. [CrossRef]

[29] Özkan DB, Onan C. Optimization of insulation thickness for different glazing areas in buildings for various climatic regions in Turkey. Appl Energy 2011;88:1331–1342. [CrossRef]

[30] Memon S, Eames PC. Predicting the solar energy and space-heating energy performance for solid-wall detached house retrofitted with the composite edge-sealed triple vacuum glazing. Energy Procedia 2017;122:565–570. [CrossRef]

[31] Feng G, Chi D, Xu X, Dou B, Sun Y, Fu Y. Study on the influence of window-wall ratio on the energy consumption of nearly zero energy buildings. Procedia Eng 2017;205:730–737. [CrossRef]

[32] El-Deeb K. Combined effect of window-to-wall ratio and wall composition on energy consumption: Where is the turning point? Proceedings of PLEA2013 - 29th Conference, Sustainable Architecture for a Renewable Future, Munich, Germany, 10-12 September 2013.

[33] Alwetaishi M. Impact of glazing to wall ratio in various climatic regions: A case study. J King Saud Univ - Eng Sci 2019;31:6–18. [CrossRef]

[34] Yang Q, Liu M, Shu C, Mmereki D, Uzzal Hossain M, Zhan X. Impact analysis of window-wall ratio on heating and cooling energy consumption of residential buildings in hot summer and cold winter zone in China. J Eng (United Kingdom) 2015;2015:538254. [CrossRef]

[35] Ghiai MM, Mahdavinia M, Parvane F, Jafarikhah S. Relation between energy consumption and window to wall ratio in high-rise office buildings in Tehran. Eur Online J Nat Soc Sci 2014;3:366–375.

[36] Shahid M, Karimi MN. Optimization of energy transmittance through building envelope for hot dry climate. J Therm Eng 2022;8:595–605. [CrossRef]

[37] Alghoul SK, Rijabo HG, Mashena ME. Energy consumption in buildings: A correlation for the influence of window to wall ratio and window orientation in Tripoli, Libya. J Build Eng 2017;11:82–86. [CrossRef]

[38] Hee WJ, Alghoul MA, Bakhtyar B, Elayeb O, Shameri MA, Alrubaih MS, et al. The role of window glazing on daylighting and energy saving in buildings. Renew Sustain Energy Rev 2015;42:323–343. [CrossRef]

[39] Ozel M. Influence of glazing area on optimum thickness of insulation for different wall orientations. Appl Therm Eng 2019;147:770–780. [CrossRef]

[40] Ozel M. Impact of glazing area on the thermal performance of buildings. Int J Ambient Energy 2022;43:2039–2055. [CrossRef]

[41] Ozel M, Ozel C. Effect of window-to-wall-area ratio on thermal performance of building wall materials in Elazığ, Turkey. PLoS One 2020;15:1–14. [CrossRef]

[42] Al-Sanea SA, Zedan MF, Al-Ajlan SA, Abdul Hadi AS. Heat transfer characteristics and optimum insulation thickness for cavity walls. J Therm Envel Build Sci 2003;26:285–307. [CrossRef]

[43] Daouas N. Impact of external longwave radiation on optimum insulation thickness in Tunisian building roofs based on a dynamic analytical model. Appl Energy 2016;177:136–148. [CrossRef]

[44] Kuehn TH, Ramsey JW, Threlkeld JL. Thermal Environment Engineering. UK: Pearson; 1998.

[45] Duffie JA, Beckman WA. Solar engineering of thermal processes. New York: John Wiley & Sons; 1991.

[46] Ozel M, Pihtili K. Effect of insulation location on the heat gain and losses for different climatic conditions. Energy Educ Sci Technol Part A-Energy Sci Res 2012;28:515–524.

[47] Ozel M, Pihtili K. Investigation of the most suitable location of insulation applying on building roof from maximum load levelling point of view. Build Environ 2007;42:2360–2368. [CrossRef]

[48] Davies MG. Useful solar gains through a south-facing window in the UK climate. Build Environ 1980;15:253–272. [CrossRef]

[49] Ozel M. Investigation of methods for minimizing heat gain and losses in the buildings with periodical temperature variation on the wall surface [Ph. D. Thesis]. Firat University Natural Sciences Institute; 2003.

[50] Ozel M, Pihtili K. Investigation of effect of wall insulation thickness on window areas. J Fac Eng Archit Gazi Univ 2008;23:655–662.

[51] Kılıç A, Öztürk A. Güneş Enerjisi. İstanbul: Kipaş Dağıtımcılık; 1983.

[52] Al-Sanea SA, Zedan MF, Al-Ajlan SA. Effect of electricity tariff on the optimum insulation-thickness in building walls as determined by a dynamic heat-transfer model. Appl Energy 2005;82:313–330. [CrossRef]

[53] Turkish State Meteorological Service. Records for weather data, Turkey, 1997-2017. Available at: https://www.mgm.gov.tr/eng/forecast-cities.aspx. Accessed Mar 11, 2025.

[54] Kontoleon KJ, Eumorfopoulou EA. The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. Build Environ 2010;45:1287–1303. [CrossRef]