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Benefiting from solar energy due to different emissivity levels of multiple glass windows for buildings

Binalarda farklı yayma oranlarına bağlı olarak çok camlı pencerelerden güneş enerjisinden yararlanma

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Abstract

In the study, firstly, heat transfer coefficients of windows were calculated according to the highest and lowest emissivity values. Secondly, monthly average solar radiation values were determined. The heat transfer coefficient calculated for double, triple and quadruple glass windows. Thirdly, the solar radiation in the south, north and east/west directions of the five climatic zones were multiplied by the shading factor, surface area and the solar energy factor of discrete buildings. Thus, the solar energy gain value for the heating period and solar energy losses for cooling period was determined. Finally, passive solar energy gains are calculated during the heating and cooling period for all climate zones. It has been calculated that in the fifth climatic zone in south direction, heat loss from windows with 0.05 emissivity can be provided with passive solar energy by 167.9% in double-glazed windows, 258.7% in triple-glazed windows and 349.1% in quadruple-glazed windows.

Keywords: Emissivity, Heat transfer coefficient of windows, Multiple glazing, Solar energy from windows

Öz

Çalışmada öncelikle en yüksek ve en düşük yayma oranlarına göre pencerelerin ısı transfer katsayıları hesaplanmıştır. İkinci olarak aylık ortalama güneş ışınımı değerleri belirlenmiştir. İkili, üçlü ve dörtlü cam pencereler için ısı transfer katsayıları hesaplanmıştır. Üçüncü olarak, beş iklim bölgesinin güney, kuzey ve doğu/batı yönündeki güneş radyasyonu, ayrı binaların gölgeleme faktörü, yüzey alanı ve güneş enerjisi faktörü ile çarpılmıştır. Böylece ısıtma periyodu için güneş enerjisi kazanç değeri ve soğutma periyodu için güneş enerjisi kayıpları belirlenmiştir. Son olarak, tüm iklim bölgeleri için ısıtma ve soğutma periyodu boyunca pasif güneş enerjisi kazanımları hesaplanmıştır. Güney yönünde beşinci iklim kuşağında 0.05 yayma oranına sahip pencerelerden ısı kaybının pasif güneş enerjisi ile çift camlı pencerelerde %167.9, üç camlı pencerelerde %258.7 ve dört camlı pencerelerde %349.1 sağlanabileceği hesaplanmıştır.

Anahtar kelimeler: Yayma oranı, Pencerelerin ısı transfer katsayısı, Çoklu cam, Pencerelerden güneş enerjisi

1 Introduction

The windows allow the use of daylight and heat caused by sunlight and also provides comfort to the indoor environment and a view to the outdoor environment [1]. One way to reduce the energy consumption of buildings can be achieved by passive design measures of windows. One of them is to benefit from alternative energy sources such as solar energy. This not only reduces the building's energy consumption, but also helps global climate change prevention efforts [2,3]. In cold climates, 10–25% of the heat lost from buildings usually occurred from windows. As to hot climates, the excessive solar radiation entering through the windows increases the cooling load [4]. Parameters such as shading, coatings on the glass with different emissivity levels, gap widths of the glass, the number of glass layers significantly affect the use of solar energy and energy passing through the window in the room [5,6,7].

When previous studies are examined, Li H et al. [8] developed a mathematical model to study the dynamic heat transfer process in the construction of outdoor walls in the hot summer and cold winter region of China. Li J et al. [9] evaluated the extensive energy consumption of the reading room in the libraries through dynamic and static simulations of lighting variation, daylight factor, and artificial lighting under different window conditions. Gondal IA et al. [2] showed that in addition to the effect of solar energy, building parameters such as roof/wall thickness, window to wall ratio and optimum window sizes can also reduce energy consumption. Udrea I and Badescu V [10] were carried out to simulations to examine the effect of various shading sources on thermal comfort, such as louvres, outdoor shadings and protrusions. Zhu Y et al. [11] measured and simulated the parameters required for the thermally efficient design and construction of rural residential buildings in north western China. Liu C et al. [12] examined the thermal and optical performance of a roof in a building containing solid and liquid phase change material (PCM). Moreover, internal

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temperature, temperature delay and total transmitted energy, solar permeability and transmitted solar energy effect were investigated. Suna Y [13] developed an innovative model (combined optical, electrical and energy model) to comprehensively evaluate the performance of an office equipped with a semi-transparent photovoltaic (STPV) window and analyse the effect of window design on overall energy efficiency. Baglivo C et al. [14] analysed the thermal behaviour of the building with TRNSYS 17 software to evaluate the indoor air temperature with various configurations such as walls, ground floor, roof, shading, windows and internal thermal loads. Maestre IR et al. [15] examined the effect of different window sizes, window orientations, typologies of shading devices, latitudes of the hemisphere sky and level of discretization on the estimation of incident direct radiation on building surfaces and the required calculation times. Khakian R [16] evaluated the energy performance of a two-storey house located in a mountainous region of Iran and examined the effect of multiple parameters such as building orientation, window to wall ratio and glass coating. Zhang G et al. [17] proposed a two-dimensional heat transfer model to numerically investigate the effect of phase change material (PCM) enriched with different types of nanoparticles on the thermal performance of windows in different seasons of the year. Altun AF and Kılıç M. [18] investigated the effect of window configuration on energy performance related to the window to wall ratio, total solar energy permeability value of glass, shading levels, orientation, geometric properties and thermo-physical properties. Košir M et al. [19] studied the interdependence of building form, orientation and window area in relation to energy consumption for heating and cooling a building in a central European climate. In the study, they found that larger window areas allowed more solar energy use. However, while this is advantageous for heating time, they have found a potential problem during the cooling season. Therefore, they recommended that appropriate shading device should be applied and the optimum solution should be obtained for the annual cumulative energy consumption of the building. Obrecht TP et al. [3] examined the deflection of the main glazed façade in the south of a family building to the other façades and how this affects the energy flow through the glass. They showed the change of optimum glass areas depending on the solar energy gains from the windows on other façades. Ashrafian T and Moazzen N [20] modelled the effect of different glass ratios and window configurations in a classroom, west and east directions, on comfort and energy demand. Xuan Q et al. [21] created and experimentally validated optical models for the Asymmetric concentrator-PV type window design, which includes the daylight function Kralj A et al. [1] studied the general configuration of six pane glass. They analysed properties such as heat transfer coefficient value, solar energy permeability, apparent permeability, solar heat gain coefficient, glass plate temperatures, vapor permeability, economic aspect and comfort. Sedaghat A et al. [22] examined the solar performance of double-glazed windows in actual working conditions in four office building with and without solar film window at the Australian College of Kuwait. Asfour OS [23] investigated the use of building integrated photovoltavices as vertical and horizontal shading devices with different tilt angles in hot climates in Saudi Arabia. Lago TGS [4] studied the thermal behaviour of a ventilated double-glazed window coated with a solar reflective film numerically and compared with the results found in the literature. Manz H and Menti UP [24] examined the energy performance of triple glasses according to the monthly average values of the internal and outdoor temperature difference and solar radiation. They calculated the gain-loss ratio depending on the glass quality and façade orientation. Frederick JE [25] developed a new model that processes, solar and longwave radiation transmission, thermal conduction and precise measurement of heat transfer to measure energy flow through single and double glazing windows. Karlsson J and Roos A. [26] studied and compared different window energy rating systems based on total solar energy permeability and thermal permeability of the window for different European climates, building types and orientations. Chandel SS ve Aggarwal RK [27] have shown that central heating systems using high cost electricity/gas/wood can be replaced with a low cost solar heating system with backup heaters. They have shown that the passive solar heating system saves on electricity required for space heating and reduces heat losses in the building by about 35%. Andersona T and Luther M [5] designed various glazing systems using different software tools to improve the thermal environment of a glass-walled commercial office. Alam MJ and Islam MA. [6] investigated the state of enhanced glazing and shading on solar energy transmitted to or lost from the room with fenestration areas for a residence in Bangladesh. Lu S et al [28] developed a solar radiation model to calculate solar energy in glass-covered buildings. Using this mathematical model, they calculated the modified solar heat gain coefficient. Kaasalainen T et al. [29] conducted studies in dynamic building simulations to examine the effects of variables such as window area, ratio, location, outdoor shading, glass properties and adjacent room condition on heating, cooling and lighting needs. Jaber S and Ajib S [30] examined the effects of windows' heat transfer coefficient value, window direction and window size on annual heating and cooling energy demand, taking into account both energy and investment costs. Carlos JS and Corvacho H [31] made simulations to estimate the heat transfer coefficient values of ventilated double windows under different window configurations and different air flow rates. Karabay H and Arıcı M [32] identified the number of glasses with thermoeconomic optimization using the degree-day method for triple and quadruple glazed windows in two different climate zones in Turkey. Kon O. [33] calculated the fuel consumption for the heating and cooling period due to double, triple and quadruple windows with emissivities between 0.0 to 1.0. Arıcı M and Kan M [7] numerically investigated the fluid flow and heat transfer properties in double, triple and quadruple glazed windows considering different emissivity coatings and gap widths of various glasses. Al-Sibai F et al. [34] presented a method that simulates in detail the heat transfer processes by conduction, convection and radiation of air gaps in different roof systems.

Kon O [35] calculated fuel consumption and emission based on outdoor walls and windows using economical optimization. Kitagawa H et al. [36] aimed to determine the window design that optimizes the indoor airflow for ventilated cooling. Multiple window types were analyzed using an experimental building in Tangerang, Indonesia. Analyzes based on convection heat transfer and standard effective temperature (SET) in the center of the room were made. Hu D and Gu Y. [37] designed a new emitter type with high emissivity and high reflectance at different wavelengths (8–13 μm & 16–25 μm) for two atmospheric windows. The designed emitter has a higher cooling potential than different types of emitters. Based on polydimethylsiloxane (PDMS) film, this new emissivity characteristic introduces a reflection window between the two windows. Heydari A et al. [38] performed cooling/heating load analyses of the modeled building using DesignBuilder software to find the optimum window configuration in the Semnan (Iran) climatic condition by changing the gap between panes and glass thickness. In the study, argon gas, krypton and air were used as insulators between the windows, and various single-glazed and double-glazed windows were examined. Zhang L et al. [39] proposed an optimization method to analyze the effect of the heat transfer coefficient on the performance of the prefabricated room envelope for hot summer and cold winter climates, in order to reduce the energy consumption for the sample room. Used in Designer's Simulation Toolkit software for an energy-consuming prefab room in Nanjing (China). Raimundo AM et al. [40] investigated the relationship between investment costs in windows, energy performance, and other related costs by contacting many window manufacturers. Calumen and Guardian Configurator software was used to make the analyzes. In the study, besides the economic benefits, the effect of the energy performance of the windows on the energy performance of the building was also examined. Shi Y et al. [41] proposed an estimation method of the composite vacuum glazing (CVG) heat transfer coefficient in their study. The theoretical calculation formula for the heat transfer coefficient of CVG has been established. Simulations were made using ANSYS. The CVG heat transfer coefficient was calculated by combining the theoretical formula and simulation results. The simulation results were compared with the experiment. Wang Z et al. [42] investigated the use of an energy-saving insulated window (ESIW), which provides energy for the protection of heat loss in winter. With DeST software, the energy consumption characteristics of the six window structure of a house with an ESIW-structure window were evaluated and comparisons were made.

The aim of the study is to calculate the change of solar energy and heat transmission for double, triple and quadruple glazed windows with coated and uncoated glasses. The internal gap of the glasses is accepted as filled with air and its thickness is chosen as 6 mm. Calculations have been made for a 0.5 m ×1 m window. According to principles for the preparation of the projects of the central heating systems (TS 2164), emissivity value of coated glass was taken as 0.05 and emissivity value of uncoated glass was 0.89. The cooling system works above 22 ^{0}C indoor air temperature and the heating system works below 19 ^{0}C indoor air temperature for residential buildings. It is considered that the building is discrete. Monthly average outdoor temperatures and monthly solar radiation values depending on the directions were taken from Turkish insulation standard (TS 825).

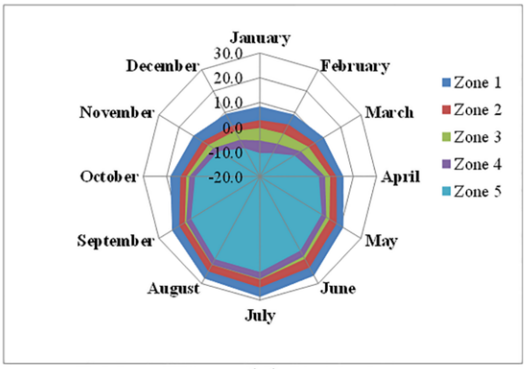
2 Methodology

Emissivity values used in the study were taken from TS 2164 (principles for the preparation of the projects of the central heating systems), the average shading factor and the solar transmission factor were taken from TS 825. In discrete buildings, the average shading factor (r_i value) was taken as 0.8 and the solar transmission factor (g_i) was 0.6.

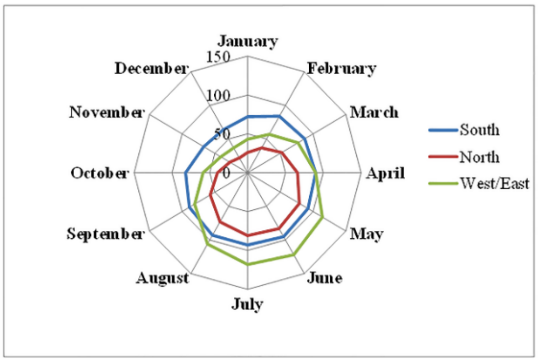
The reason for choosing a discrete building in the study is that the shading factor is the highest building type. In the study, the temperature value was chosen as 19 ^{0}C for the heating period and 22 ^{0}C for cooling period in different climate zones. It is thought that heating is done below 19 ^{0}C outdoor air temperature and cooling is done above 22 ^{0}C outdoor air temperature. In solar energy gain or loss calculations, south, north and west/east directions are taken into consideration. It is assumed that the window internal gap is filled with air.

2.1 Meteorological data for different climate zones

Outdoor air temperatures and solar radiation values in different directions according to different climate zones used in the calculations are taken from the Turkish standard TS 825 [43]. In Figure 1, a) Outdoor temperatures for different climate zones b) Solar radiation values depending on different directions are shown according to TS 825.



(a)



(b)

Figure 1. a) Outdoor temperatures for different climate zones b) Solar radiation values depending on different directions

2.2 Calculation of convection heat transfer coefficient

The following equations were used to find the convection heat transfer coefficient of the air gap of windows with multiple glazing [34,45].

Grashof number;

$$Gr = \frac{g.L^3.\beta.(T_s - T_0)}{\vartheta^2} \quad (1)$$

Here, g is the gravitational acceleration, T_s is the surface temperature, T_0 is the outdoor air temperature (ambient temperature), ϑ is the kinematic viscosity, β is the volumetric expansion coefficient, α is the thermal diffusivity, L is the air layer thickness (natural convection is the distance between hot and cold surfaces in heat transfer in closed gaps).

Rayleigh number;

$$Ra=Gr.Pr \quad (2)$$

$$Pr=\frac{\vartheta}{\alpha} \quad (3)$$

Here, Gr is grashof number and Pr is prandtl number.

Nusselt number;

$$\text{If} \quad Ra<10^3 ; \quad Nu=1 \quad (4)$$

$$\text{If} \quad 10^3<Ra<10^4 \text{ and } \frac{H}{L}<83 ; \quad Nu=0.38.Ra^{0.25}.\left(\frac{H}{L}\right)^{-0.25} \quad (5)$$

$$\text{If} \quad 10^4<Ra<10^7 \text{ and } \frac{H}{L}<83; \quad Nu=0.42.\,Pr^{0.012}.Ra^{0.25}.\left(\frac{H}{L}\right)^{-0.25} \quad (6)$$

$$\text{If} \quad 10^7<Ra<10^9; \; Nu=0.049.Ra^{0.33} \quad (7)$$

Convection heat transfer coefficient;

$$h=\frac{Nu.\lambda_a}{L} \quad (8)$$

Here, λ_a is heat conduction coefficient of the air (W/m.K), L is the air layer thickness and h is the convection heat transfer coefficient. When Nu=1, conduction heat transfer occurs [34,45]. In Table 1, reference outdoor temperature values are given in the calculation of convection heat transfer coefficient.

Table 1. Reference outdoor temperatures for calculating convection heat transfer coefficient [44]

Zone	Temperature (^{0}C)
1	3
2	-6
3	-12
4	-18
5	-27

2.3. Calculation of general heat transfer coefficient for windows

General heat transfer coefficient for multiple glazed windows [7,32,33,35];

$$U_w=\frac{1}{\frac{1}{h_i.A}+\frac{c}{k_{glass}.A}+\frac{1}{\left(U_{1\text{-}2,cond}+U_{1\text{-}2conv}+U_{1\text{-}2,rad}\right)}+\frac{c}{k_{glass}.A}+\frac{1}{h_0.A}} \quad (9)$$

Here, the $U_{1\text{-}2cond}$ is conduction heat transfer coefficient, $U_{1\text{-}2conv}$ is convection heat transfer coefficient and the $U_{1\text{-}2rad}$ is radiation heat coefficient between the inner surfaces of the outdoor glass,

$$U_{1\text{-}2,cond}=\frac{1}{\frac{L}{A.k_{air}}+(n\text{-}2)\left(\frac{c}{A.k_{glass}}+\frac{L}{A.k_{air}}\right)} \quad (10)$$

$$U_{1\text{-}2,conv}=\frac{1}{\frac{1}{h.A}+(n\text{-}2)\left(\frac{1}{h.A}\right)} \quad (11)$$

$$U_{1\text{-}2,rad}=\frac{1}{\frac{2(1\text{-}\varepsilon)}{(A.\varepsilon)}+\frac{2(n\text{-}2)(1\text{-}\varepsilon)}{(A.\varepsilon)}+\frac{(n\text{-}1)}{(F_{ij}.A)}}\cdot\frac{\sigma(T_1^4\text{-}T_2^4)}{(T_1\text{-}T_2)} \quad (12)$$

Here, radiation heat transfer and conduction or convection heat transfer occur between glasses. Here, h is convection heat transfer coefficient, n is the number of glass layer, L is air gap thickness, A is the surface area, ε is emissivity, σ is Stefan-Boltzman constant, for uncoated glass window; h_o=34 W/m^2.K and h_i=8.29 W/m^2.K and for coated glass window; h_o=34 W/m^2.K and h_i=4.4 W/m^2.K internal and outdoor convection heat transfer coefficient, kglass is the heat conduction coefficient of glass (k_{glass}=0.92 W/m.K), kair is the conduction heat transfer coefficient of air, (1- ε)/(εA) and $1/F_{ij}$ are surface and area radiation resistance. Fij was taken as 1, and glass thickness was assumed as 4 mm. T_1 and T_2 are the internal surface temperature of windows [7,32,33,35,45].

2.4. Solar energy and heat transmission calculation for multi glass windows

Solar energy transition from through the windows [24,30,31,43];

$$E_s=r_i.g_i.I_{sr}.A \quad (13)$$

Here, r_i is average shading factor, g_i is solar energy transmission factor, and I_{gm} is monthly average solar radiation intensity depending on different directions.

Heat transition from the through the windows;

$$Q=U_w.\Delta T.A=U_w.(T_i\text{-}T_0).A \quad (14)$$

Here, U_w is heat transfer coefficient for multiple glazing window, ΔT is temperature differences between indoor and outdoor air and A is the surface area of window. T_i is indoor air temperature, T_0 is outdoor air temperature.

Solar energy transition and heat transition ratio;

$$\tau = \frac{E_s}{Q} = \frac{r_i \cdot g_i \cdot I_g \cdot A}{U_w \cdot \Delta T \cdot A} \qquad (15)$$

Here, τ is shown as positive due to the gain of solar energy during the winter period and negative for the multiple glazed windows as there is heat transfer (heat gain) from inside to outside environment. During the summer period, solar energy flux from outdoor to indoor environments, so energy consumption is required for cooling. Therefore, both are shown as a negative. While the total energy needs decrease due to solar energy gain for the winter period and it increases with the contribution of solar energy for the summer period [43]. In the literature, the temperature values for cooling season varying between 20 to 26 ^{0}C. In this study, 22 ^{0}C was accepted.

If T_i<19 ^{0}C ; heating is done (16)

If 19 ^{0}C<T_i<22 ^{0}C ; there is no need for heating or cooling (17)

If 22 ^{0}C<T_i; cooling is done (18)

The general heat transfer coefficient was calculated between 1.563 to 1.602 W/K for double-glazed windows with 0.89 emissivity. For double-glazed windows with 0.05 emissivity, it was calculated between 0.734 and 0.863 W/K. It was estimated between 1.069 to 1.080 W/K for triple-glazed windows with 0.89 emissivity and between 0.464 to 0.560 W/K with 0.05 emissivity. It was calculated between 0.800 to 0.816 W/K for quadruple-glazed windows with 0.89 emissivity and between 0.332 to 0.415 W/K with 0.05 emissivity. These values are given in Fig. 2.

3 Results and discussions

When the indoor set-point temperature is taken as 19 ^{0}C for heating and 22 ^{0}C for cooling, cooling is performed in the 1st and 2nd climate zones in the summer period. In the third, fourth and fifth climate zones, only heating is performed.

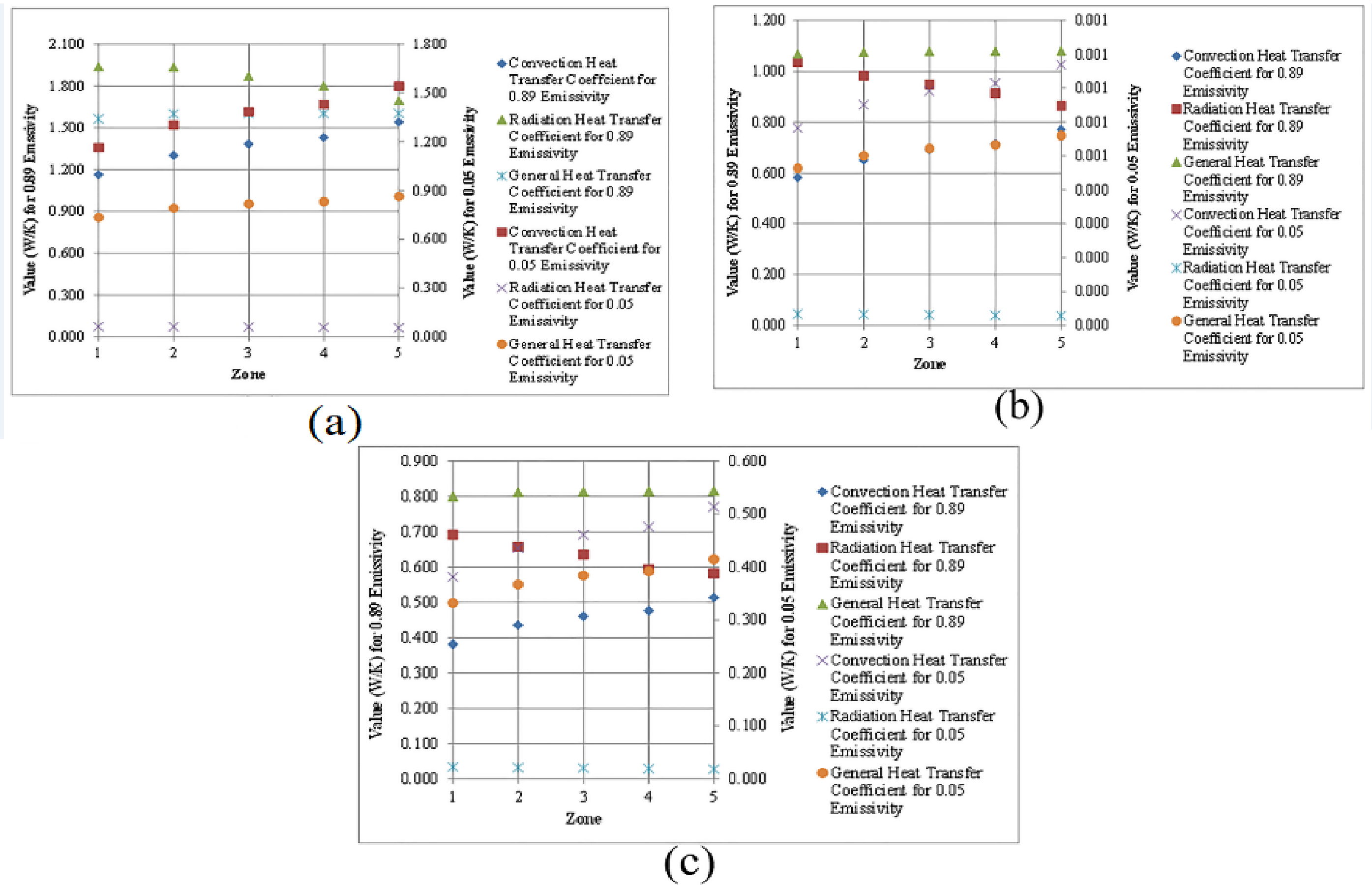


Figure 2. Change of heat transfer coefficients of a) double-glazed b) triple-glazed d) quadruple-glazed windows according to climate zones

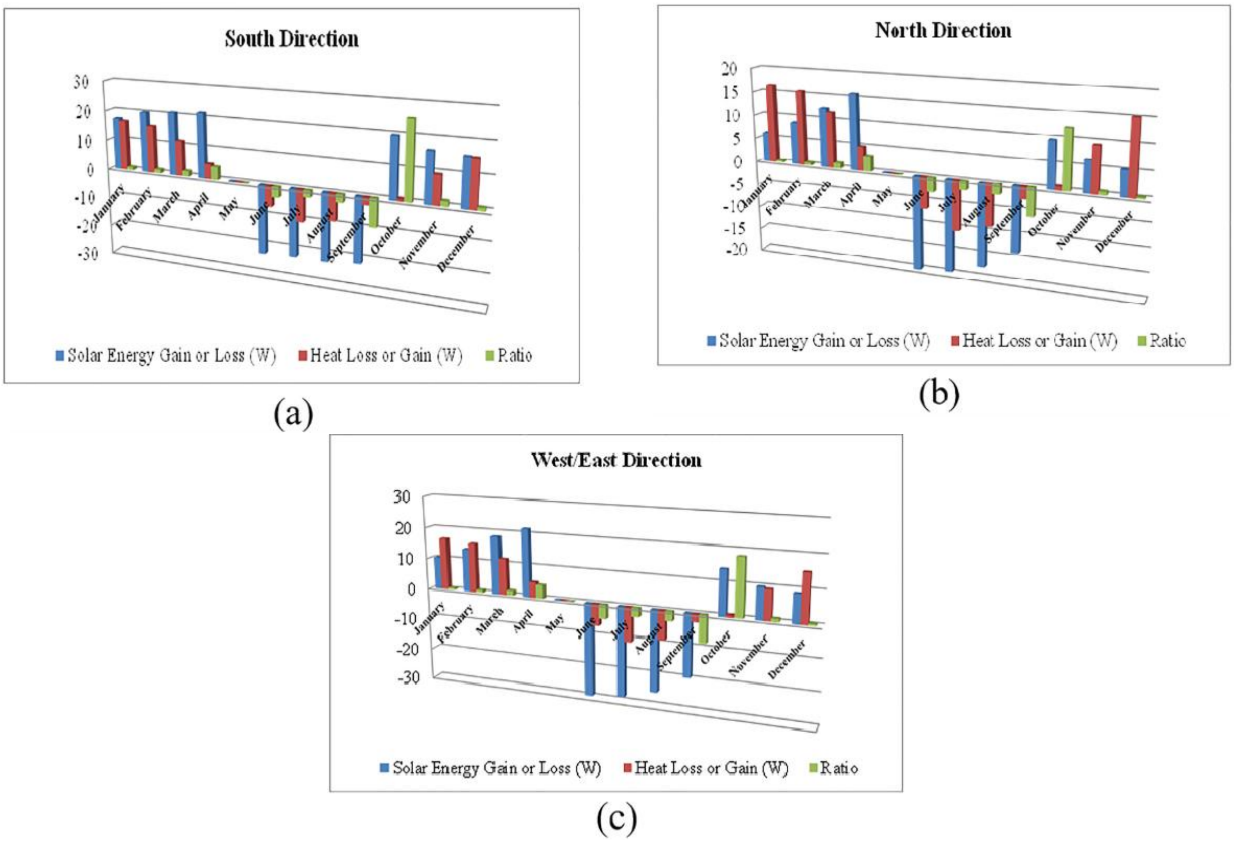


Figure 3. The change of solar energy gain or loss and heat loss or gain in the 1st zone for the uncoated (ε=0.89) double-glazed windows a) South Direction, b) North Direction and c) West/East Direction

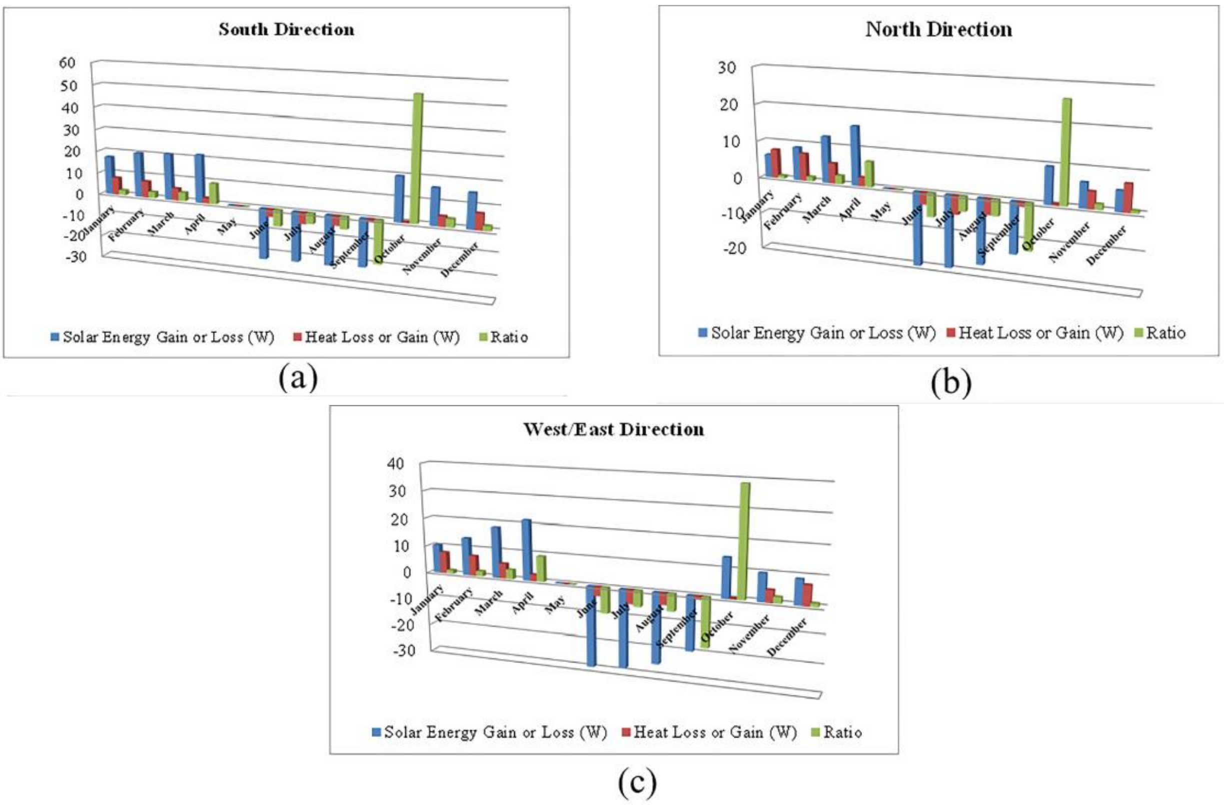


Figure 4. The change of solar energy gain or loss and heat loss or gain in the 1st zone for the coated (ε=0.05) double-glazed windows a) South Direction, b) North Direction and c) West/East Direction

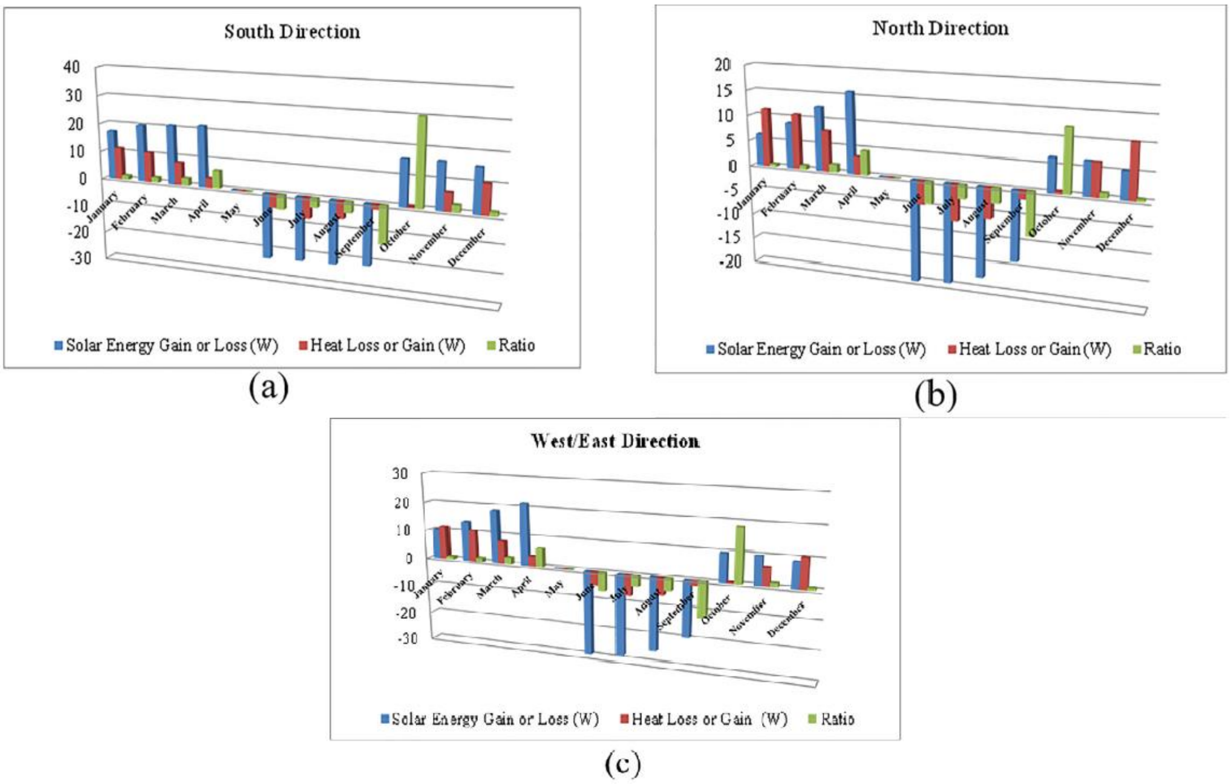


Figure 5. The change of solar energy gain or loss and heat loss or gain in the 1st zone for the uncoated (ε=0.89) triple-glazed windows a) South Direction, b) North Direction and c) West/East Direction

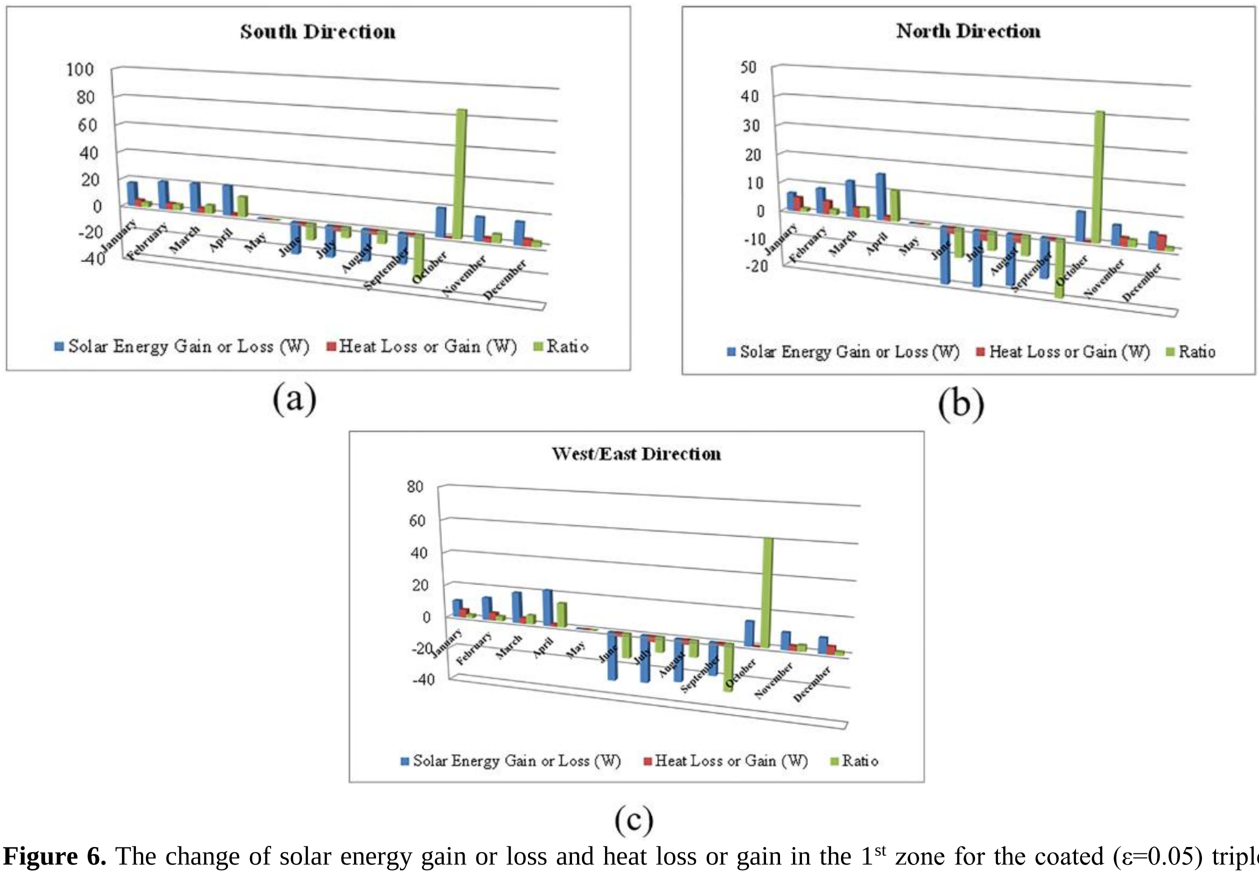


Figure 6. The change of solar energy gain or loss and heat loss or gain in the 1st zone for the coated (ε=0.05) triple-glazed windows a) South Direction, b) North Direction and c) West/East Direction

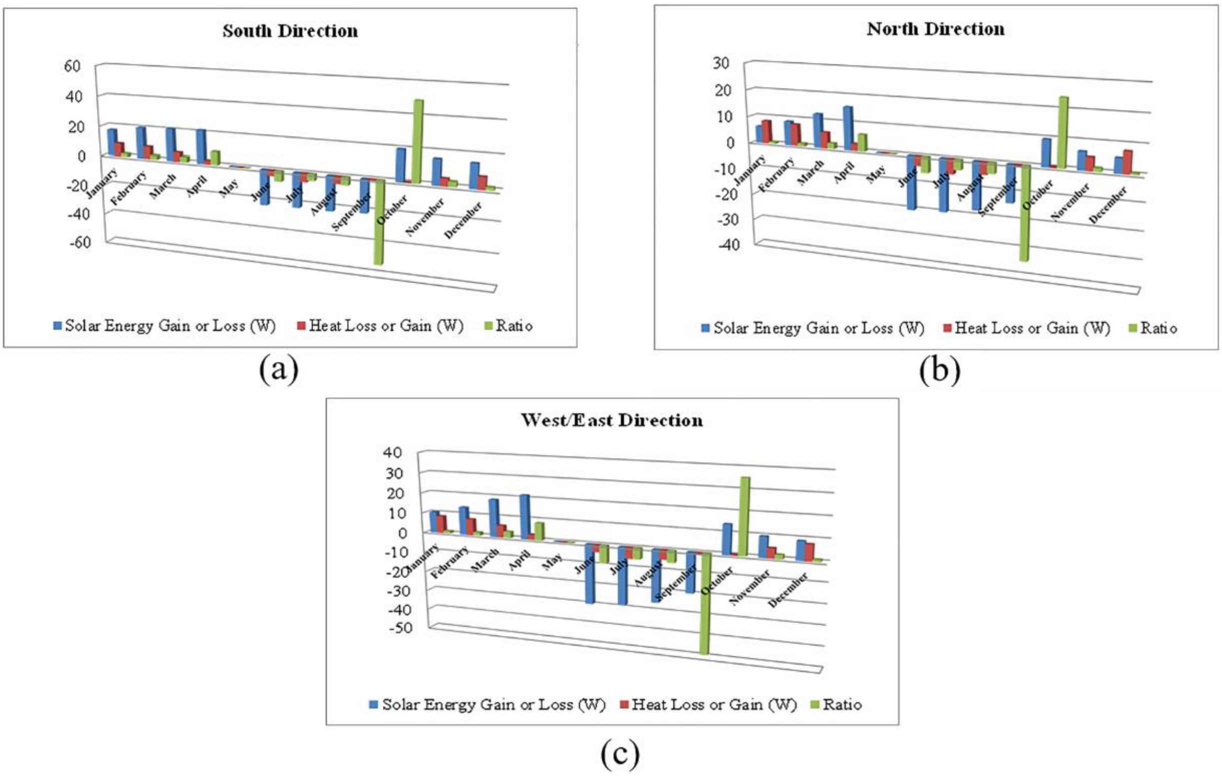


Figure 7. The change of solar energy gain or loss and heat loss or gain in the 1st zone for the uncoated (ε=0.89) quadruple-glazed windows a) South Direction, b) North Direction and c) West/East Direction

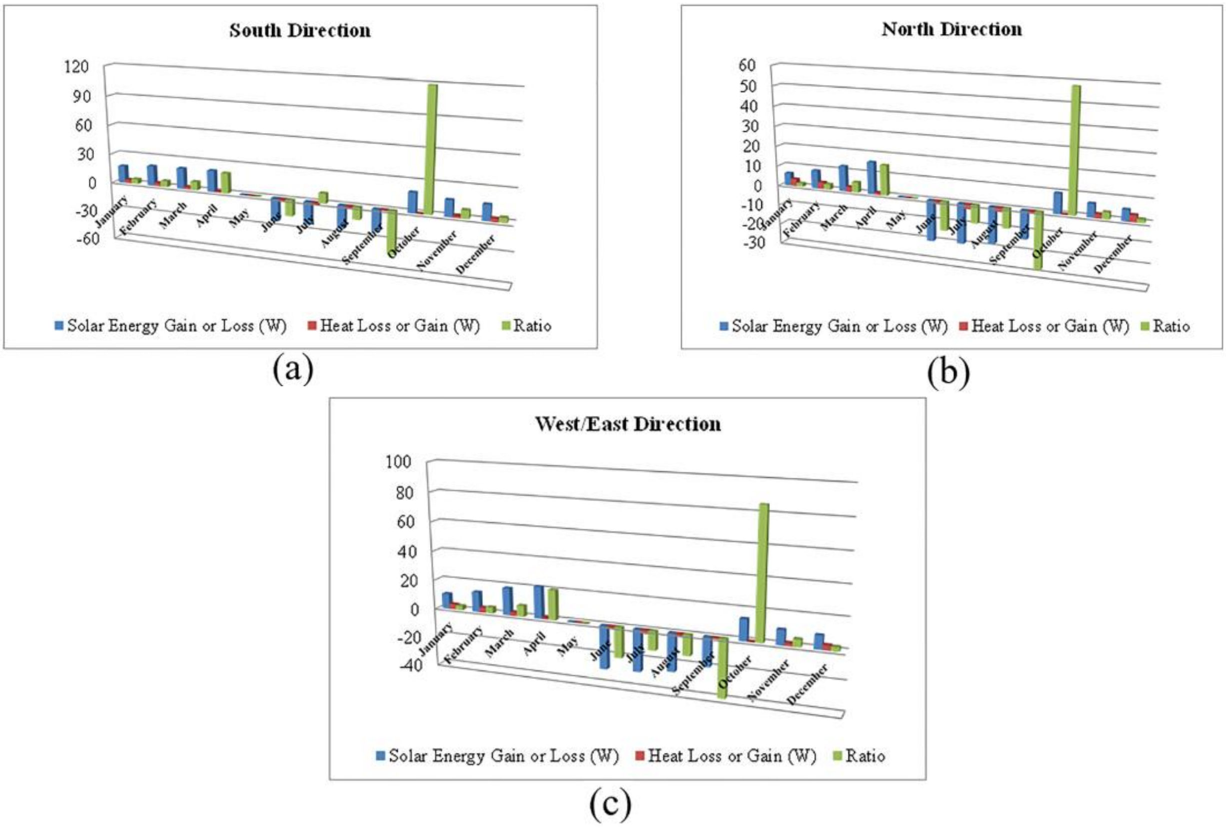


Figure 8. The change of solar energy gain or loss and heat loss or gain in the 1st zone for the coated (ε=0.05) quadruple-glazed windows a) South Direction, b) North Direction and c) West/East Direction

In the 1st climate zone, heating is performed in January, February, March, April, October, November and December, when the outdoor temperature is below 19 ^{0}C. Cooling is carried out in June, July, August and September at the outdoor temperatures above 22 °C. In May, since the outdoor temperature is between 19 ^{0}C and 22 ^{0}C, there is no need for heating and cooling. In the 2nd climate zone, heating is done in May because the outdoor temperature is below 19 ^{0}C and the cooling is done only in June, July and August. In the 3rd and 4th climate zones, only heating is done. In July and August, since the outdoor temperature is between 19 ^{0}C and 22 ^{0}C, heating and cooling is not performed. In the 5th climate zone, heating is carried out in all months of the year.

In the 1st climate zone in winter, the heat loss from uncoated double-glazed window with 0.89 emissivity was calculated as 45.796 W, while it was found as 21.513 W for a coated double-glazed window with 0.05 emissivity. It was calculated as 31.321 W for the uncoated triple-glazed window with 0.89 emissivity and found as 13.596 W for the coated triple-glazed window with 0.05 emissivity. It was figured out as 24.240 W for the uncoated quadruple-glazed window with 0.89 emissivity and 9.728 W for the coated quadruple-glazed window with 0.05 emissivity. From Figure 3 to Figure 8, solar energy gain or loss, heat loss or heat gain and their ratios are shown related to the amount of solar energy and heat transfer depending on the south, north and west / east direction; for winter and summer period in the 1st climate zone.For the winter months, the maximum of total heat loss was calculated as 267.537 W for double-glazed windows with 0.89 emissivity in the 5th climate zone and the minimum of total heat loss was 74.087 W in 1st climate zone. For double-glazed windows with 0.05 emissivity, the highest heat loss was 144.121 W in the 5th climate zone and the lowest was 34.793 W in the 1st climate zone. For triple-glazed windows with 0.89 emissivity, the highest total of heat loss was found to be 180.360 W in the 5th climate zone and the lowest was 50.671 W in the 1st climate zone. For windows with 0.05 emissivity, the highest value was found as 93.520 W in the 5th climate zone and the lowest value was 21.995 W in the 1stclimate zone. For quadruple-glazed windows with 0.89 emissivity, the maximum total of heat loss was determined as 136.274 W in the 5th climate zone and the minimum was 37.920 W in the 1st climate zone. For the windows with 0.05 emissivity, 69.308 W in the 5th climate zone with the highest value and 15.738 W in the 1st climate zone with the lowest value. These values are shown in Appendix 2, Appendix 3 and Appendix 4.

For the summer period, the maximum heat gain was found as 28.291 W for double-glazed windows with 0.89 emissivity in the 1st climate zone and the lowest total of heat gain was 9.115 W in 2nd climate zone. For double-glazed windows with 0.05 emissivity, the highest total of heat gain was 13.286 W in the 1st climate zone and the lowest was 4.509 W in the 2nd climate zone. For triple-glazed windows with 0.89 emissivity, the highest total heat gain was determined as 19.350 W in the 1st climate zone and the lowest was 6.129 W in the 2nd climate zone. For windows with 0.05 emissivity, the highest value was calculated as 8.399 W in the 1st climate zone and the lowest value was 2.856 W in the 2nd climate zone. For quadruple-glazed windows with 0.89 emissivity, the maximum total of heat gain was calculated as 13.680 W in the 1st climate zone and the minimum was 4.629 W in the 2nd climate zone. For the windows with 0.05 emissivity, 6.010 W in the 1st climate zone with the highest value and 2.092 W in the 2nd climate zone with the lowest value. These values are given in Appendix 2, Appendix 3 and Appendix 4.

For the winter months, the average of the highest solar energy gain/heat loss ratio for double-glazed windows with 0.89 emissivity is calculated as 7.792 W in the west/east direction in the 5th climate zone and the lowest average ratio was 2.072 W in the north direction in the 2nd climate zone. For windows with 0.05 emissivity, the maximum average ratio was 14.823 W in the west/east direction in the 5th climate zone and the minimum average ratio was 3.834 W in the north direction in the 4th climate zone. For triple-glazed windows with 0.89 emissivity, the average of the highest solar energy gain/heat loss ratio was found as 11.858 W in the west/east direction in the 5th climate zone and the average of the lowest solar energy gain/heat loss ratio was 2.245 W in the north direction in the 4th climate zone. The average of the highest solar energy gain/heat loss ratio for windows with 0.05 emissivity was 22.869 W in the west/east direction in the 5th climate zone and the lowest was 4.639 W in the north direction in the 4th climate zone. For quadruple-glazed windows with 0.89 emissivity, the highest average ratio was calculated as 15.711 W in the west/east direction in the 5th climate zone and the lowest average ratio was 3.033 W in the north direction in the 4th climate zone. For windows with 0.05 emissivity, 30.860 W in the west/east direction in the 5th climate zone with the highest value and 6.305 W in the north direction in the 4th climate zone with the lowest value. The values are given in Appendix 2, Appendix 3 and Appendix 4.

For the summer period, the highest average solar energy loss/heat gain ratio for double-glazed windows with 0.89 emissivity was found as 16.541 W in the west/east direction in the 2nd climate zone and the lowest ratio was 3.164 W in the north direction in the 1st climate zone. For windows with 0.05 emissivity, the highest average ratio was calculated as 33.423 W in the west/east direction in the 1st climate zone and the minimum average ratio was 6.738 W in the north direction in the 1st climate zone. For triple-glazed windows with 0.89 emissivity, the average of the highest solar energy loss/heat gain ratio was estimated as 24.598 W in the west/east direction in the 2nd climate zone and the lowest average of solar energy loss/heat gain ratio was 4.626 W in the north direction in the 2nd climate zone. The average of the highest solar energy loss/heat gain ratio for windows with 0.05 emissivity was determined as 55.742 W in the west/east direction in the 1st climate zone and the lowest was 10.659 W in the north direction in the 1st climate zone. For quadruple-glazed windows with 0.89 emissivity, the highest average ratio was calculated as 32.588 W in the west/east direction in the 2nd climate zone and the lowest average ratio was 11.882 W in the north direction in the 1st climate zone. For windows with 0.05 emissivity, 71.693 W in the west/east direction in the 1st climate zone with the highest value and 14.986 W in the north direction in the 1st climate zone with the lowest value. The values are given in Appendix 2, Appendix 3 and Appendix 4.

For the winter months, the maximum total of solar energy gain and total of heat loss difference for double-glazed windows with 0.89 emissivity was found as 56.953 W in the south direction in the 1st climate zone and the lowest was -113.217 W in the north direction in the 5th climate zone. For windows with 0.05 emissivity, the highest value was calculated as 109.534 W in the south direction in the 3rd climate zone and the lowest was in the north direction in the 4th climate zone with 5.402 W. For triple-glazed windows with 0.89 emissivity, the highest solar energy gain and heat loss difference was 80.369 W in the south direction in the 1st climate zone and -26.040 W in the north direction in the 5th climate zone at the lowest value. For windows with 0.05 emissivity, the highest and lowest values were found as 148.400 W in the south direction in the 5th climate zone and 42.805 W in the 1st climate zone, respectively. For quadruple-glazed windows with 0.89 emissivity, the maximum solar energy gain and heat loss difference was 109.854 W in the south direction in the 3rd climate zone and 7.009 W in the north direction in the 4th climate zone as the lowest value. For windows with 0.05 emissivity, the highest was 172.612 W in the south direction and the lowest was 49.062 W in the north direction in the 1st climate zone. The values were given in detail in Appendix 2, Appendix 3 and Appendix 4.

For the summer period, the highest total of solar energy loss and heat gain was calculated as -130.771 W in the west/east direction in the 1st zone and was found as -65.995 W in the north direction in the 2nd zon for double-glazed windows with 0.89 emissivity. For windows with 0.05 emissivity, it is calculated as -115.766 W in the west/east direction in the 1st zone and -61.389 W in the north direction in the 2nd zone. For triple-glazed windows with 0.89 emissivity, the maximum total of solar energy loss and heat gain was determined as -121.830 W in the west/east direction and the minimum was -63.009 W in the 2nd zone. For windows with 0.05 emissivity, it was found as -142.776 W in the west/east direction in the 1st zone and -59.736 W in the north direction in the 2nd zone. For quadruple-glazed windows with 0.89 emissivity, the highest value was calculated as -108.490 W in the west/east direction in the 1st zone and the lowest value was -61.509 W in the north direction in the 2nd zone. For windows with 0.05 emissivity, the highest total of solar energy loss and heat gain was -116.160 W in the west/east direction in the 1st zone and -58.972 W in the north direction in the 2nd zone. More details were given in Appendix 2, Appendix 3 and Appendix 4.

The zone with the highest heat loss is the 5thzone for double, triple and quadruple-glazed windows while the lowest zone is the 1st zone during the winter months. The reason for this is that in the 5th climate zone, heating is carried out in the whole year. Besides, in the 1st climate zone, seven months of heating and four months of cooling are performed and in the 2nd climate zone, heating for eight months and cooling for three months is done. In the 3rd and 4th climate zones, only heating is done for ten months of the year. There is no cooling in the 3rd, 4th and 5th climatic zones. While the number of months heating increases from climate zone 1 to 5, the number of months with cooling decreases.

The highest total solar energy gain was calculated as 241.920 W and the lowest was 131.040 W for double, triple and quadruple glazed windows with emissivities of 0.89 and 0.05 in the south direction for the winter months. The highest total solar energy gain for north direction was determined as 154.320 W and the lowest was 64.800 W. The highest total solar energy gain for the west/east direction was found as 226.800 W and 96.960 W.

For the summer months, the highest total solar energy gain was calculated as 88.800 W and the lowest was 67.440 W for double, triple and quadruple glazed windows with emissivities of 0.89 and 0.05 in the south direction. The highest total solar energy gain for north direction was determined as 70.560 W and the lowest was 56.880 W. The highest total solar energy gain for the west/east direction was found as 102.480 W and 83.040 W.

Solar energy gain/heat loss ratio in winter and solar energy loss/heat gain ratio change in summer depends on whether the 1st climate zone is the hottest and the 5th climate zone is the coldest zone and the lowest solar energy is in the north direction. While these ratios are higher in the south direction in the 1st climate zone, the west/east direction is higher in other climate zones. These rates are calculated at a much higher value in west/east direction.

The heat loss increases from climate zone 1st to 5th during the winter months. In summer period, heat gain (cooling process) is higher in the 1st climate zone, while it is less in the 2nd climate zone.

Solar energy gain/heat loss ratio increases as the outdoor temperature increases in the winter months when heating is performed. In the summer months when cooling is performed, as the outdoor temperature increases, the rate of solar energy loss/heat gain decreases.

The heat loss is lower in the coated glass windows with 0.05 emissivity for the winter months compared to the uncoated glass windows with 0.89 emissivity. Accordingly, the solar energy gain/heat loss ratio is higher. In summer, heat gain occurs at a lower rate. Accordingly, the rate of solar energy loss/heat gain is higher.

4 Conclusions

The results obtained by the relationship between solar energy and heat loss due to coated and uncoated double, triple, and quadruple glazed windows with different emissivity:

The convection heat transfer coefficient increases from climate zones 1st to 5th and radiation heat transfer coefficient reduces.

As the number of glass increases, convection, radiation and general heat transfer coefficient decreases.

For uncoated glasses with 0.89 emissivity compared to coated glasses with 0.05 emissivity; radiation and general heat transfer coefficient are of higher value.

For coated glasses with 0.05 emissivity compared to uncoated glasses with 0.89 emissivity; since heat loss in winter and heat gain occur lower in summer, solar energy gain/heat loss rate in winter and solar energy loss/heat gain rate in summer is higher. Thus, while benefiting from solar energy more in winter, the effect of solar energy is reduced in summer.

For the heating period, as the number of glasses increases, the heat loss decreases. The rate of benefiting from solar energy increases. Thus, the rate of solar energy gain/heat loss increases. Heat gain decreases for the cooling period. Thus, the less solar energy gain occurs and the less cooling process is performed.

The highest energy saving is provided in quadruple-glazed windows with 0.05 emissivity. The quadruple-glazed window has a high solar energy gain/heat loss ratio for the heating period. For the cooling period, it has a low solar energy loss/heat gain ratio.

The highest solar gain (loss in summer months) occurs on the south direction and the lowest on the north direction (loss in summer months).

Considering the annual cumulative energy total in the 1st climate zone where heating and cooling are performed together, 92.2% of the heat loss in the double-glazed windows with 0.89 emissivity in the south direction is provided by solar energy. Also 196.4% of the heat loss is provided in 0.05 emissivity glass. Similarly, in the 2nd climate zone where heating and cooling are performed together, 72.5% of heat loss is provided in double-glazed windows with 0.89 emissivity, and 145.3% is provided in windows with 0.05 emissivity. It is seen that there is more solar energy gain than heat loss in windows with 0.05 emissivity. Thus, the gain obtained is a passive energy gain that can be used to reduce the overall energy loss of the whole building.

When the 3rd, 4th, and 5th climate zones examined where only heating is performed; in the 5th climate zone at the south direction, it is calculated that 167.9% of the heat loss in the double-glazed, 258.7% of the heat loss in the triple-glazed windows, and 349.1% of the heat loss in the quadruple-glazed windows with 0.05 emissivity can be passively provided by solar energy. This is a significant amount to reduce the energy loss of the entire building.

When all calculations are considered, quadruple-glazed windows with 0.05 emissivity are the most suitable glazing system in terms of annual energy gain for all climate zones considering the entire building.

Conflict of interest

The authors declare no conflict of interest

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Appendix-1. The solar energy gain or loss, heat loss or gain and their ratios and energy exchange for uncoated and coated double-glazed windows

Parameter	Winter										Summer			
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 1		Zone 2	
	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)
South Direction														
Solar Energy Gain or Loss Total (W)	131.040	131.040	153.040	153.840	197.280	197.280	197.280	197.280	241.920	241.920	-88.800	-88.800	-67.440	-67.440
Heat Loss or Gain Total (W)	34.793	74.087	63.439	128.241	87.746	171.840	111.958	215.657	144.121	267.537	-13.286	-28.291	-4.509	-9.115
Average Ratio	11.063	5.193	5.745	2.848	8.902	4.549	4.105	2.131	12.640	6.804	-9.148	-4.296	-26.526	-13.127
Difference for Winter and Total for Summer (W)	96.247	56.953	89.601	25.599	109.534	25.440	85.322	-18.377	97.799	-25.617	-102.086	-117.091	-71.949	-76.555
North Direction														
Solar Energy Gain or Loss Total (W)	64.800	64.800	83.760	83.760	117.360	117.360	117.360	117.360	154.320	154.320	-70.560	-70.560	-56.880	-56.880
Heat Loss or Gain Total (W)	34.793	74.087	63.439	128.241	87.746	171.840	111.958	215.657	144.121	267.537	-13.286	-28.291	-4.509	-9.115
Average Ratio	5.632	2.644	4.188	2.072	6.977	3.566	3.834	1.544	10.206	5.494	-6.738	-3.164	-22.803	-11.285
Difference for Winter and Total for Summer (W)	30.007	-9.287	20.321	-44.481	29.614	-54.480	5.402	-98.297	10.199	-113.21	-83.846	-98.851	-61.389	-65.995
West/East Direction														
Solar Energy Gain or Loss Total (W)	96.960	96.960	124.320	124.320	173.040	173.040	173.040	173.040	226.800	226.800	-102.48	-102.48	-83.040	-83.040
Heat Loss or Gain Total (W)	34.793	74.087	63.439	128.241	87.746	171.840	111.958	215.657	144.121	267.537	-13.286	-28.291	-4.509	-9.115
Average Ratio	8.265	3.880	6.071	3.003	10.197	5.211	4.332	2.248	14.823	7.992	-9.720	-4.564	-33.423	-16.541
Difference for Winter and Total for Summer (W)	62.167	22.873	60.881	-3.921	85.294	1.200	61.082	-42.617	82.679	-40.737	-115.76	-130.77	-87.549	-92.155

* Since there is solar energy gain and heat loss in winter, it is defined with a plus sign. In summer, it is defined with a minus sign because there is solar energy loss and heat gain. The ratio is the solar energy gain / heat loss ratio for the winter period in which the heating is performed, the solar energy loss / heat gain ratio for the summer period when the cooling is performed.

Appendix-2. The solar energy gain or loss, heat loss or gain and their ratios and energy exchange for uncoated and coated triple-glazed windows

Parameter	Winter										Summer			
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 1		Zone 2	
	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)
South Direction														
Solar Energy Gain or Loss Total (W)	131.040	131.040	153.040	153.040	197.280	197.280	197.280	197.280	241.920	241.920	-88.800	-88.800	-67.440	-67.440
Heat Loss or Gain Total (W)	21.995	50.671	40.181	86.217	56.064	115.778	71.795	153.110	93.520	180.360	-8.399	-19.350	-2.856	-6.129
Average Ratio	17.500	6.630	9.070	4.228	13.942	6.751	6.401	3.067	19.469	10.095	-14.472	-6.281	-41.858	-19.521
Difference for Winter and Total for Summer (W)	109.045	80.369	112.859	66.823	141.216	81.502	125.485	44.170	148.400	61.560	-97.199	-108.15	-70.296	-73.569
North Direction														
Solar Energy Gain or Loss Total (W)	64.800	64.800	83.760	83.760	117.360	117.360	117.360	117.360	154.320	154.320	-70.560	-70.560	-56.880	-56.880
Heat Loss or Gain Total (W)	21.995	50.671	40.181	86.217	56.064	115.778	71.795	153.110	93.520	180.360	-8.399	-19.350	-2.856	-6.129
Average Ratio	8.909	3.032	6.612	3.082	10.929	5.292	4.639	2.245	15.721	8.152	-10.659	-4.626	-35.983	-16.782
Difference for Winter and Total for Summer (W)	42.805	14.129	43.579	-2.457	61.296	1.582	45.565	-35.750	60.800	-26.040	-78.959	-89.910	-59.736	-63.009
West/East Direction														
Solar Energy Gain or Loss Total (W)	96.960	96.960	124.320	124.320	173.040	173.040	173.040	173.040	226.800	226.800	-102.48	-102.48	-83.040	-83.040
Heat Loss or Gain Total (W)	21.995	50.671	40.181	86.217	56.064	116.138	71.795	153.110	93.520	180.360	-8.399	-19.350	-2.856	-6.129
Average Ratio	13.074	4.518	9.584	4.467	15.973	7.735	6.754	3.268	22.869	11.858	-15.376	-6.673	-52.742	-24.598
Difference for Winter and Total for Summer (W)	74.965	46.289	84.139	38.103	116.976	56.902	101.245	19.930	133.280	46.440	-110.87	-121.83	-142.77	-89.169

* Since there is solar energy gain and heat loss in winter, it is defined with a plus sign. In summer, it is defined with a minus sign because there is solar energy loss and heat gain. The ratio is the solar energy gain / heat loss ratio for the winter period in which the heating is performed, the solar energy loss / heat gain ratio for the summer period when the cooling is performed.

Appendix-3. The solar energy gain or loss, heat loss or gain and their ratios and energy exchange for uncoated and coated quadruple-glazed windows

Parameter	Winter										Summer			
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 1		Zone 2	
	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)	Coated (ε=0.05)	Uncoated (ε=0.89)
South Direction														
Solar Energy Gain or Loss Total (W)	131.040	131.040	153.040	152.400	197.280	197.280	197.280	197.280	241.920	241.920	-88.800	-88.800	-67.440	-67.440
Heat Loss or Gain Total (W)	15.738	37.920	29.435	65.123	41.244	87.426	52.806	109.784	69.308	136.274	-6.010	-13.680	-2.092	-4.629
Average Ratio	24.457	10.150	12.382	5.587	18.955	8.942	8.700	4.185	26.271	13.375	-15.208	-17.294	-57.112	-25.862
Difference for Winter and Total for Summer (W)	115.302	93.120	123.605	87.277	156.036	109.854	144.474	87.496	172.612	105.646	-94.810	-102.48	-69.532	-72.069
North Direction														
Solar Energy Gain or Loss Total (W)	64.800	64.800	83.760	82.560	117.360	117.360	117.360	117.360	154.320	154.320	-70.560	-70.560	-56.88	-56.880
Heat Loss or Gain Total (W)	15.738	37.920	29.435	65.123	41.244	87.426	52.806	109.784	69.308	136.274	-6.010	-13.680	-2.092	-4.629
Average Ratio	12.450	5.167	9.026	4.062	14.857	7.009	6.305	3.033	21.214	10.800	-14.896	-11.882	-49.097	-22.233
Difference for Winter and Total for Summer (W)	49.062	26.880	54.325	17.437	76.116	29.934	64.554	7.576	85.012	18.046	-76.570	-84.240	-58.972	-61.509
West/East Direction														
Solar Energy Gain or Loss Total (W)	96.960	96.960	124.320	124.280	173.040	173.040	173.040	173.040	226.800	226.800	-102.48	-102.48	-83.04	-83.040
Heat Loss or Gain Total (W)	15.738	37.920	33.887	65.123	41.244	87.426	52.806	109.784	69.308	136.274	-6.010	-13.680	-2.092	-4.629
Average Ratio	18.270	7.583	12.912	5.913	21.715	10.244	9.180	4.390	30.860	15.711	-21.488	-17.014	-71.963	-32.588
Difference for Winter and Total for Summer (W)	81.222	59.040	90.433	59.157	131.796	85.614	120.234	63.256	157.492	90.526	-108.49	-116.16	-85.132	-87.669

* Since there is solar energy gain and heat loss in winter, it is defined with a plus sign. In summer, it is defined with a minus sign because there is solar energy loss and heat gain. The ratio is the solar energy gain / heat loss ratio for the winter period in which the heating is performed, the solar energy loss / heat gain ratio for the summer period when the cooling is performed.