NUMERICAL ANALYSIS OF THERMAL PERFORMANCE OF GLAZING SYSTEMS

A Thesis Submitted to
the Graduate School of Engineering and Sciences of
İzmir Institute of Technology
in Partial Fullfilment of the Requirements for the Degree of

MASTER OF SCIENCE

in Architecture

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July 2019
İZMİR

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ACKNOWLEDGMENTS

I would like to thank and express my very great appreciation to my supervisor Prof. Dr. Tahsin Başaran for his constructive supports with the scientific guidance, his patience and encouragement during my study.

I also would like to thank to Prof. Dr. Tuğçe Kazanasmaz and Asst. Prof. Dr. Ziya Haktan Karadeniz for their guiding comments and suggestions for this thesis.

I would like to thank to my faithful friends for being with me during my education period and throughout of my life. I also would like to thank my colleagues at our company of Yağmurcan İnşaat Mimarlık.

Finally, I am deeply grateful to my dear parents, Ayşegül and Adem Şahin, and my brother Can Şahin for their continuous support, patience and encouragement in every stage of my education and all my life.

ABSTRACT

NUMERICAL ANALYSIS OF THERMAL PERFORMANCE OF GLAZING SYSTEMS

Thermal performance of different glazing systems have been investigated with a comprehensive parametric study numerically. In order to analyze the heat transfer through the windows, CFD simulations have been performed considering many affecting parameters. The aim of the study is to determine the appropriate window configurations according to the different cities that have different climatic conditions of Turkey which are: Ağrı, Sivas, Amasya and İskenderun. For this purpose, the glazing part of the window has been analyzed because of having low thermal resistance due to the gap widths, temperature differences and the emissivity values.

Four physical models of glazing systems were designed. The thickness of glazing units is 4 mm and the height is 1 m as a constant. For investigating the effect of the cavity dimension on the heat transfer, two gap widths usually used, are determined and combined in different ways which as 12–12 mm, 16–16 mm, 12–16 mm and 16–12 mm. Different boundary conditions are defined according to ambient temperature of inside and outside. Radiation heat transfer is included in the calculations and various low-e coatings are defined to analyze the radiation effect on the heat transfer coefficient.

As a result of this study, temperature and velocity profiles are different in all scenarios. The effect of gap width on the U-value is more distinguished in the low temperature difference. Heat loss can be minimized significantly with using low-e material and the emissivity value is more effective on the wider gap widths. It is also shown that the optimum air layer thickness of the triple pane window differ from the temperature difference significantly. The highest U-values were obtained in 12-12 mm gap width glass. It was determined that the heat losses can be reduced by using 16-12 mm gap width glass about 2% and 8% in cold regions and in warm regions respectively.

ÖZET

CAM SİSTEMLERİNİN ISIL PERFORMANSININ SAYISAL ANALİZİ

Pencere camlarından kaynaklanan ısı kayıplarının binaların enerji performansına etkisi enerji verimliliği konusunda dikkate alınması gereken bir meseledir. Bu çalışmanın amacı cam sistemlerinin ısıl performansını çeşitli parametreler üzerinden incelemektir. Kapsamlı bir ısı transfer analizi için CFD simülasyon metodu kullanılmıştır. Amaç farklı iklim şartlarına sahip Türkiye'de bulunan 4 şehrin; Ağrı, Sivas, Amasya ve İskenderun'un ortalama kış sıcaklıklarına göre belirlenen koşullarda, ısıl performans açısından en uygun pencere şeklini belirlemektir.

Çalışmada üçlü cam sistemi üzerinden gerçekleşen ısı transferi ve cam boşluklarındaki akış incelenmiştir. Bunun için 4 farklı fiziksel model oluşturulmuştur. Cam ünitelerin kalınlıkları 4 mm, yükseklikleri ise 1 m olarak belirlenmiştir. Cam üniteleri arasındaki boşluğun ısı transferine etkisini değerlendirmek için uygulama alanlarında en çok tercih edilen 12 ve 16 mm'lik boşluk genişlikleri seçilip 4 farklı şekilde bir araya getirilmiştir. Belirlenen senaryolar 12-12 mm, 16-16 mm, 12-16 mm ve 16-12 mm boşluk genişliğine sahip üçlü camlardır. Dıştaki ve içteki sıcaklık durumlarına göre çeşitli sınır koşulları belirlenmiştir. Cam yüzeyler arasındaki boşlukta 1 atmosfer başınçta kuru hava olduğu varsayılmıştır ve havanın özellikleri ortalama sıcaklığa göre belirlenmiştir. Radyasyon ile gerçekleşen ısı transferi hesaplamalara dahil edilmiştir. Farklı değerlerde düşük yayınım kaplamaları cam yüzeylerine tanımlanarak, radyasyonun ısı transferine etkisi gösterilmiştir.

Bu çalışmanın sonunda, literatürdeki benzer çalışmalarda da gösterildiği gibi boşluk genişliğini 12 mm'den sonra arttırmak U değerinde önemli bir azalışa sebep olmamaktadır. Boşluk genişliğinin ısı transferindeki etkisi düşük sıcaklık farklarında daha çok fark edilir. Cam yüzeylerin emissivite değerini düşürmek ısı transfer miktarını önemli ölçüde azaltır ve büyük boşluk genişliklerinde daha etkilidir. Bu nedenle düşük emissivite kaplamalı camlarda en yüksek U değerleri 12-12 mm boşluk genişlikli camlarda elde edilmiş ve 16-12 mm boşluk genişliğine sahip cam kullanılarak soğuk bölgelerde ısı kayıplarının 2% ve sıcak bölgelerde ise 8% oranında azaltılabileceği gösterilmiştir.

To my dear parents,

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CHAPTER 1

INTRODUCTION

This chapter consists of two main sections. These are argument of the study and the procedure of the study.

1.1. Argument

Increasing energy demand in the world has also increased energy consumption rapidly and problems such as bad weather, climate change and depletion of natural resources have started to affect both human health and environment negatively. Thus, the issue of “energy conservation” has gained importance for energy researchers. As a result of the development of construction industry in recent years, building’s energy consumption has become a main problem in this field. Because, it causes, even in developed economies, %40 of the total energy consumption in the world.[1] Due to these concerns of environment, improving energy efficiency in the building sector and providing comfortable and healthy indoor environment has come into prominence. In this respect, there have been several studies that addressed the importance of the buildings about the energy savings.

The Kyoto Protocol was accepted at the conference held in Kyoto in 1997 to challenge global warming and climate change and it was effectuated in 2005. The aim is to reduce carbon dioxide emissions to the atmosphere and energy consumption. 191 countries and EU are state party for the protocol, currently.[2] In 2002, the EU directive (EPBD) on the energy performance of buildings, inspired by the Kyoto Protocol, was published and reorganized in 2010 (European Energy Performance of Buildings 2010/31/AB). In the meantime construction regulations were developed and building energy certification schemes were established. In addition, in the published directive the importance of “Nearly Zero-Energy Buildings (NZEB)” was emphasized. NZEB is defined as buildings that consume zero or very low energy. According to this, all buildings to be constructed in EU member countries will be constructed as “Zero-Energy” before the 31st of December, 2020. The deadline for public buildings is 31st of

December, 2018. This is the most important substance that differs with the Turkish legislation on energy efficiency. Turkey became a state party to the Kyoto Protocol in 2009, but there is no obligation on a numerical reduction of greenhouse gas emissions for Turkey. With the Energy Efficiency Law (Enerji Verimliliği Kanunu) that came into force in Turkey in 2007, the strategic targets related to energy efficiency are determined. Buildings have the most energy saving potential in Turkey. Therefore, energy efficiency in the building sector was taken into consideration and soon after TS825 (TS825 "Binalarda Isı Yalıtım Kuralları" Standardı) was revised and Building Energy Performance Regulation (Binalarda Enerji Performansı Yönetmeliği) came into force in 2009.[3] However, the percentage of energy consumed for heating and cooling of buildings in Turkey is quite high in total energy consumption. The data obtained from the "Türkiye Enerji ve Tabii Kaynaklar Bakanlığı" website, the 82 percent of energy consumption in buildings is for heating. While comparing with the building in the same climatic conditions and in the same usage area in France, Germany, England and Sweden, the building in Turkey consumes 2 or 3 times more energy. It shows that the insulation is not given enough importance in Turkey.[4] Therefore, the standards to be revised according to European standards and attention should be paid to the energy performance of both existing and new buildings.

Improving the building energy performance means that the energy required to the heating, cooling and ventilating the building is minimized. For all these, the insulation of the building should be the good enough. Because every heat loss from the building or heat gain to the building increases the energy consumption. Heat transfer from the building should be avoided as much as possible to keep the temperature inside optimally. Walls and floors are more favorable in terms of thermal insulation and prevent the heat transfer with good insulation considerably. However, the windows are the weakest parts in the building fabric because of their poor insulation characteristic. The 25 percent of heat loss of the building from the windows.[5] Therefore, improving the thermal performance of the windows increases also building energy performance significantly.

Windows are essential elements of buildings about architectural, social, psychological and environmental aspects. Because of that, the performance studies of the windows in terms of energy, user comfort requirements and all the necessary physical features have increased recently. In addition to basic functions such as natural lighting, visual relationship with external environment and natural ventilation, the window systems have been designed to have features such as thermal comfort, solar control, airtightness, waterproofing, noise control, security, economy, aesthetics, durability and sustainability. Especially the properties of high insulation, low leakage rates and large area of windows have become a necessity in building design. So, the study about the window performance increased and organizations that make classification according to the performance criteria such as heat transfer coefficient (U-value), solar heat gain coefficient (SHGC) and visible transmittance (VT) of the windows have emerged. The National Fenestration Rating Council (NFRC) determines the energy performance value in multiple categories for windows and it awards certificate to the windows also. This organization is based on ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards. In Turkey, there is no specific regulation for the window standard. Only in TS 825, for the four climatic zones in Turkey, the window heat transfer coefficient is determined as 2.4 W/m^{2}K for the frame and glass.[6] As can be seen from the Table 1.1 the windows used in Turkey are not energy efficient enough comparing with European countries. Furthermore, energy efficient window standards should vary depend on climate regions.

Table 1.1. The window glass insulation standards of different countries (W/m^{2}K) (Source: [7] modified from NSG Flat Glass Report 2010 and TSE 825 Standards)

Germany		2009	2012
New Construction	Obligatory	1.1 – 1.3	0.7 – 1.0
Renovation	Obligatory	1.3	0.8 – 1.1
A.B.D.		2010	2013
Housing (New Construction)	Obligatory	2.27	1.82
Non-domestic (New Construction)	Obligatory	2.67	2.04
Korea		2009	2010
Housing (New Construction)	Obligatory	1.8	1.4
Non-domestic (New Construction)	Obligatory	3	2.1
Japan		Since 1999	
New Construction / Renovation	Recommended	2.33 – 6.51	
Turkey		1999	2008
Housing (New Construction)	Obligatory	2.8	2.4
Non-domestic (New Construction)	Obligatory	2.8	2.1

The housing in Turkey, 88% of the building has single glass and only 12% of the building has insulating glass. In EU countries, the use of insulating glass is over 50%.[4] The use of double glazing is still the most widely used method since it provides a thermal resistance compared to a single glass. However, with increasing energy consumption and comfort demands, the study about improving thermal performance of windows is in progress. Low emissivity coatings, solar control coatings, anti-reflective surface treatments, infrared transparent glasses, use of heavier gases in the window cavities and etc. are the technological improvement about this field of study. However, most of the studies were based on the thermal performance of double glazed windows. In recent years, studies on triple and quadruple pane windows have started and thus it has been shown that the use of standard double glazed windows is insufficient in terms of energy efficiency, especially in cold climates.[8,9,10]

In line with these recent and ongoing studies, this thesis presents the thermal performance analysis of triple glazed windows. The aim of the study is to facilitate the selection of the optimum window according to the temperature difference that may occur in different cities in Turkey. The glazing part of the window has the most effect on the thermal performance of the window. Because it covers about 75% of the window area and it has low thermal resistance. Therefore, only the glazing part was taken into account for the heat transfer analysis in this study. Heat losses from the window frame, energy losses due to infiltration and heat gain from the sun have not been included in the calculations of this study.

It is predicted that the thermal performance of the window can be improved by determining the properties such as gap widths, emissivity values of the glass panes properly. So, four different scenarios were determined according to gap widths which are usually used. For the analyzing of heat transfer through triple glazing systems, the gap widths will be used differently as 12-12 mm, 16-16 mm,12-16 mm and 16-12 mm. In previous studies about this research area, these combinations have not been tried.

A comprehensive study has been conducted to analyze fluid movements, natural convection, conduction and radiation heat transfer in triple glazed windows. For this purpose, a commercial program ANSYS FLUENT 19.1 CFD code, which is based on finite volume method, is used. The use of Computational Fluid Dynamics (CFD) modeling is the best solution for numerical analysis of fluid flow and heat transfer problem. It is also well documented in window research areas. In the light of all this information, this study also aims to be premise for future studies.

1.2. Procedure

The study was carried out five phases. In the first phase, a comprehensive survey was conducted on the energy efficiency of the window and its impact on the building energy consumption. The laws and regulations related to window energy efficiency were mentioned.

In the second phase, the historical evaluation of windows and glasses is explained. Window and glazing systems are examined according to physical requirements that affect the energy performance. And also components and types of the window system are represented.

In the third, the thermal performance of glazing part of the windows is pointed out and examined in detail. The previous studies about the thermal performance of glazing systems are analyzed. The deficiencies were determined in literature studies.

In the fourth, the physical models of the windows were designed in the ANSYS Fluent Software. The material and methodology of the study was presented in this section. Boundary conditions of analysis were defined and solution method was explained.

In the fifth, the computation results of all scenarios were discussed. The optimum glazing type attempted to determine according to different climatic conditions of defined cities. The effects of the studied parameters on heat transfer were analyzed. In the last chapter the results of the study were evaluated.

CHAPTER 2

LITERATURE SURVEY

In this chapter, the literature survey of the study is presented. In the first section, the historical evolution of glass and windows are mentioned briefly. The developments of the glass and window productions methods are explained. Then, window systems are examined about physical properties that affect energy performance. Following sections include technical information about window systems and its manufacturing process. As mentioned at the end of the chapter, this study primarily takes in consideration to the glazing part of the window and its effect on the energy efficiency of the windows.

2.1. Historical Evolution of Glass and Windows

The history of the glass dates back older than the window. Glass findings made of natural glass to be used as cutting tools in the 5000 B.C. were found. The earliest findings of the old man-made glass object were from 3500 B.C. The first windows were created by covering the holes in the wall with the cloth, wood or animal fleece.[11] The first use of glass in the window has been in 1500 B.C. In the early 1800s, a production technique has emerged that was created to produce larger glass. This allowed for the expansion of the openings in the facades. Crystal Palace, built in London in 1851, is one of the first examples of using large surface glass in the facade.[12] The flat glass production process was developed by Alastair Pilkington in the late 1950s, resulting in the production of larger amounts of glass is provided at low cost. The technique which is called float glass technique, flat glass can be produced up to 3210 x 6000 mm. With this development at that time, criticism of the energy consumption associated with a facade of a building completely covered with glass has increased. And with the energy crisis in the 1970s, the study on energy efficient glasses were started. As the developments in glass architecture gained importance in the 1980s, studies on ecological and eco-friendly construction techniques gained speed and different coating materials were tried on glass surfaces.[12,13]

2.2. Physical Performance Requirements of Window Systems

The main tasks of the windows of the building are natural lighting, ventilation and sunlight gain, besides the windows are the most important element affecting the energy performance of buildings. The use of windows in buildings has increased with the developing technology in recent years. Wide openings are used because of providing aesthetic perception, landscape and natural lighting especially in multi-storey office or residential buildings. Therefore, the need for energy conservation of windows increases day by day. With the properly window design, the amount of consumed energy and the costs of heating, cooling, lighting and ventilating for the building can be reduced by 10-40%.[14] Important criteria of windows for providing user comfort conditions and improving energy performance of buildings are; thermal transmittance (U value), air tightness, condensation resistance, waterproofing, natural lighting, visible transmission, solar control and solar gain and acoustic control.

2.2.1. Overall Heat Transfer Coefficient – U Value

The U-value (thermal transmittance) is the overall heat transfer coefficient and is a measurement that how much heat is transferred from windows per square meter in a given temperature difference. The lower U-value indicates the better heat insulation is achieved for the window.

The U-value represents the heat transfer rate through a window in the absence of sunlight, air infiltration and surface condensation. The total thermal transmittance of windows, U_o, can be calculated by knowing the three components of windows separate contribution. These components are the glazing unit, frame and the spacer between panes. Using area-weighted the overall U-factor is estimated by the calculation of ASHRAE Handbook of Fundamentals (ASHRAE – 2009) [15]:

$$U_o = \frac{(U_{cg}A_{cg} + U_{eg}A_{eg} + U_f A_f)}{A_{pf}} \tag{2.1}$$

where

A_{cg} = projected area of glazing, m^2

A_{eg} = projected area of edge-seal, m^2

A_f = projected area of frame, m^2

A_{pf} = projected area of the entire window, m^2

U_{cg} = centre-glass U-value, W/m^{2}K

U_{eg} = edge-of-glass U-value, W/m^{2}K

U_f= frame U-value, W/m^{2}K

U_o= overall U-value of the window, W/m^{2}K

Besides, U-value can be obtained by combining heat transfer mechanisms of radiation, convection and conduction through multiple-glazed windows (W/m^2°C). The U-value can be calculated, as below:

$$\frac{1}{U} = \frac{1}{h_o} + \frac{1}{h_t} + \frac{1}{h_i} \tag{2.2}$$

where h_i and h_o are the internal and external glass surface convective heat transfer coefficients, HTC, respectively and h_t is the heat transfer coefficient of multiple glazed unit. As known climate, wind condition, etc. of the air have the significant effect on the heat transfer. Thus, the external heat transfer coefficient (h_o) can be change according to the wind speed and building orientation. It varies between 12.5 W/m^{2}K and 34 W/m^{2}K. The internal HTC (h_i) depends on the internal radiation HTC and internal convection HTC. It has also standardised value of 8.29 W/m^{2}K for ordinary glass surfaces and natural convection. Last, h_t depends on number of window cavities, total thickness of glass panes, thermal resistivity of glass, infill gas heat transfer coefficient (h_s) which is combined convection HTC and radiation HTC within the cavity.[16]

If the window panes have no reflective coating, the air space heat transfer coefficient (h_s) of the window is 7.4 W/m^{2}K. It can be change depends on the reflective coatings, air space thickness, air space temperatures and temperature difference as reported in.[15] Calculation of the U-value of the multiple-glazed windows is explained in detail in the section of 3.3.1.

2.2.2. Properties of Thermal Radiation

Thermal radiation is the type of the electromagnetic radiation related with the heat transfer. As a result of energy transitions of molecules, atoms, and electrons of a substance, thermal radiation is emitted. With increasing temperature, thermal radiation emission increases. Thermal radiation is the portion of the electromagnetic spectrum between 0.1 and 100 µm shown in Figure 2.1.

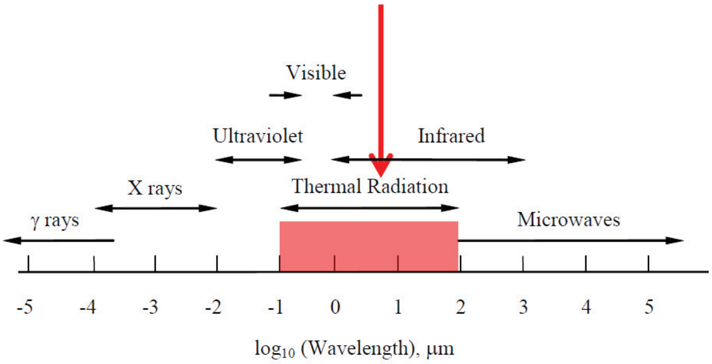


Figure 2.1. Thermal radiation portion in electromagnetic spectrum
(Source: Introduction to ANSYS Fluent[17])

Radiation heat transfer takes place in solid, liquid and gases materials. Differently from other heat transfer mechanisms which are conduction and convection, radiation can be occurred also in an evacuated space. For normal float glass windows, more than half of the heat is lost by radiation. However, most of the studies about thermal performance of windows do not consider heat transfer by radiation.

Emissivity value is one of the radiative properties that have significant effects on U-value of the window. Emissivity is described as diffusion-radiation coefficient and 0.84 for the ordinary uncoated glass. The body that emits ideal energy is called the blackbody and its emissivity value is 1. A blackbody emits radiation energy uniformly from all directions. The other substances have the emissivity value between 0 to 1.[15] Properties of the radiation emission characteristics are absorptivity (α), reflectivity (ρ) and transmissivity (τ). When radiation coming to the surface, some part of it is reflected, some part of it is absorbed and the other is transmitted. And, the sum of them is equal to the incident radiation. These values are specified the characteristics of the material such as transparency etc.

2.2.3. Infiltration and Exfiltration

Air infiltration means air leaks into a building from outside while air exfiltration means air leaks from building to the outside. For the energy efficiency of the building, it is essential to control how air moves into and out of the building. Because, air infiltration and exfiltration impact building's energy cost. And also, all buildings must have sufficient ventilation. That's why air infiltration and exfiltration must be taken into consideration.

Small leaks of air around window frames, under doors and under floorboards are regarded as infiltration. So, the windows are the key elements that affect building's comfort in this subject. And there are several methods for calculating the change in infiltration rate in the building when windows are replaced. One of the studies for optimizing infiltration rate studied on a new replacement window infiltration rate model. The study showed replacement windows can significantly reduce infiltration rates.[18]

There are other factors that affect infiltration rates which are building structure, air-tightness, wind velocity and direction, pressure differences between inside and outside. In winter time infiltration increases because of increased wind speed and increased temperature differences between internal and external environments of the buildings. Because the increase in temperature difference causes the pressure difference to increase. Especially in high-rise buildings, this pressure difference causes stack effect that increases infiltration also.

2.2.4. Internal Surface Condensation

Condensation occurs usually in winter time when the outside air temperature is lower than the inside air temperature. Due to the windows that are usually closed in winter, the density of water vapour inside the house increases. So, it can causes condensation on the window surface which usually happens at the relatively colder place.

Internal surface condensation depends on various factors of the indoor temperature, humidity and outdoor temperature.[19] It can reduce with some design strategies such as with using insulation windows, installation of suitable heating, cooling and ventilation system and using thermally insulated window frame. In addition, reducing the amount of internal water vapour can be achieved by a user's precautions such as ventilating the house, using aspirator and keep the rooms at the same temperature. In addition to these, in the study about surface condensation on the glazing, the inner surface condensation of the aluminium separator between the glass panes was evaluated to prevent condensation on the windows. It has been shown that surface condensation is prevented by reducing the internal surface temperature by an applied insulation spacer.[19]

In some climatic zones, condensation can occurs also on the outer surface of the windows. It can be seen in the night when the relative humidity of the air is high. This case shows also the thermal performance of the windows.[20] Therefore using a window with high thermal performance reduces heat loss as well as prevents condensation on the glass surfaces.

2.2.5. Waterproofing

Windows must be protected against climate events. Water leaks may occur especially from the window frame due to rain and moisture. It affects the performance of window system negatively. For this reason, the details of the frame profile are important to ensure waterproofing. So window frame must be designed in such a way that it can collect the leaking water in a channel and throw it out. Besides, the connection of the wall and sash frame, sash and casement connections and glass and sash joints are the details that need attention. Necessary waterproofing should be provided in these areas. With the new technological developments, waterproofing can also provide with plastic surfaces waterproofing coatings can be applied to surfaces such as glass, wood and metal.

2.2.6. Natural Lighting

Natural lighting is the basic necessity for people who need daylight. It has been proven by the studies that sunlight is the greatest support to human health and positive effects on the mood. Therefore, it is necessary to make optimum use of daylight in the buildings where people spend most of their lives. In general, the ratio of the window area to the room floor area varies between 1/3 and 1/10. In study rooms and offices, this ratio can be in the range of 1/3 - 1/5 and in the living room and bedrooms can be in the range of 1/5 – 1/10.[21] It has been observed that daylight has both social and physiological advantages especially on the employees. In addition, it is possible to minimize the artificial lighting energy which constitutes 33% of the energy consumed in the buildings with providing natural lighting.

The windows, as the elements that provide natural lighting in the buildings, directly affect the comfort requirement of the user and the building's energy performance. Therefore, in the design of lighting, window design and performance is as important as the building orientation and location. Providing sufficient daylight in living areas is a complex problem. Uncontrolled sunlight leads to overheating and glare problems in particular. In order to prevent this, it is necessary to pay attention to the daylight transmittance value of the window glass in window design. Daylight transmittance value (VT) is the percentage of daylight is the percentage of sunlight that transmitted from the glass in the wavelength of 380 to 780 nm.[22] This value may vary according to the type, number and surface coatings types of the glass. The high VT value reduces the need for artificial lighting when causes problems such as glare, increasing the amount of energy required for heating and cooling. The climate is an important factor in determining the light transmittance value of the glass. While light transmission is expected to be high in the northern regions, it is demanded that the light transmittance is low to prevent excessive brightness in the southern regions.[23] Daylight transmittance outward reflection values of glass are determined according to EN410 standard.

2.2.7. Solar Control and Solar Gains

Especially in the regions that have high solar radiation intensity, it is necessary to avoid overheating by taking the sunlight inside in a controlled manner. Thus, glazing material must be designed according to provide optimum daylight and solar heat gain.

Solar heat gain coefficient (SHGC) is the ratio of the solar heat measured by a given type of glass to the solar heat incident on the glazing unit. It is calculated as:

$$SHGC = \frac{Solar\ heat\ gain\ through\ the\ window}{Solar\ radiation\ incident\ on\ the\ window} = \frac{\dot{q}_{solar,gain}}{\dot{q}_{solar,incident}} \qquad (2.3)$$

The coating materials on either side of the glass and other related factors affect the measured values of SHGC. Radiation reaches the earth's surface in three ways; direct radiation, diffuse radiation and reflected radiation from the surroundings. Solar radiation incident on the single clear glass surface is shown in the Figure 2.2. The glass is 6 mm thickness. About 8 percent of the radiation is reflected, about 12 percent is absorbed and the remaining part is transmitted to the inside. The sum of the reflected, transmitted and absorbed solar radiation equals to the incident solar radiation. The transmitted part of the radiation and the inward transfer of absorbed radiation can be described as the heat gain for the building.[24]

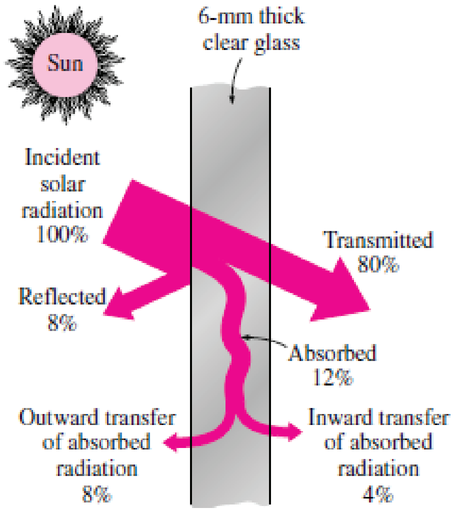


Figure 2.2. Distribution of solar radiation incident on a clear glass (Source: Çengel[24])

The value of SHGC is between 0 and 1. When the value of SHGC is calculated, the total solar heat gain through window can be calculated as well:

$$\dot{Q}_{solar,gain} = SHGC\ x\ A_{glazing}\ x\ \dot{q}_{solar,incident} \quad (W) \qquad (2.4)$$

Where, $A_{glazing}$ is the area of glazing and $\dot{q}_{solar,incident}$ is the solar heat flux. Incident radiation angle, the thickness of the glazing unit and the coating materials are other parameters affecting the solar heat gain. There are other factors that affect the energy efficiency of the glazing unit such as; Shading Coefficient (SC), Solar Cooling Load (SCL) and Visible Light Transmission (VLT). Shading is provided with internal shading and/or external shading devices. The external shading is usually preferred because it reduces heating and cooling loads sufficiently. Internal shading reduces the solar heat gain with reflecting radiation and it can provide the thermal comfort inside. Therefore, low-emissivity (low-e) coatings are preferred to reduce heat gain by radiation in summer and heat loss in winter. It is generally used on the inner surface of the windows. Tinted glass and glass coated are also used.[24]

Nowadays, with the selective-permeable surface coated glasses passes the visible part of the solar radiation in the wavelength range of 380-780 nm. However, it acts like an opaque material against the wavelength range of 780-2500 nm due to the thermal effect of the infrared radiation. So, this produced coated has the high performance for the solar control.[12]

2.2.8. Acoustic performance

Windows are more vulnerable than walls in terms of sound insulation also. The sound insulation provided by a single glazed window is only 20 dB when for a wall the insulation rate is between 35 and 56 dB.[21] Therefore it is necessary to provide a good acoustic performance for windows for the user's comfort. Because noise pollution is harmful to human health. It can causes concentration problems for users, prevent hearing and reduce the productivity.

The acoustic performance of the glass is related to the glass thickness, the elasticity of the glass, the composition of the insulating glass, the width of the gas filled cavity and the type of gas used. The most practical way to prevent outside noise from entering the inside is to increase the glass thickness. For double glazing windows can also be used with different thickness glasses. And acoustic insulation can also change the gas in the cavity with heavier gases for multiple pane windows.

There are acoustic laminated glasses specially produced for environments with high noise levels. They are produced by combining two glass plates with a sound-absorbing layer with the help of heat and pressure. Thus, it is obtained a high acoustic performance glass. These glasses also can be used for a safety and security glasses.

2.3. Frame and Glazing Systems of Windows

Frame and glazing system of windows is described as a fenestration system. A fenestration system includes glazing, frames that hold the glazing, mullions, muntin bars, dividers and other attachments or shading devices. It has usually planar, transparent or translucent glazing part. It can be fixed or operable.[15]

2.3.1. Frame Systems

Frame systems are the carrier systems of the glass and it serves the connection between the glasses and building. Generally, it has lower thermal insulation values than glasses. There are various types of frames produced according to the type of building and user's needs.

Until the 17th century, frame systems made of only wood. However it can be produced from many different materials currently. With the Industrial Revolution, the production of steel frames started. And towards the middle of the 20th century, the use aluminum frames increased rapidly.[25] Most commonly used frames; wooden frames, aluminum frames and PVC frames at the present time.

2.3.1.1. Wooden Frames

Wood is a material that has been used for window frames for centuries because of its many advantages. Wooden frames are low thermal conductivity, easy to shape, compatible with nature and resistant to condensation. However it should be carefully protected against external factors. Painting, coating with a fiberglass or vinyl material are the method for protecting wood from moisture and decay. In addition it is important also in production which wood is used and whether it is damaged or not.[25]

Because of low thermal conductivity of the wooden frame, it prevents heat losses considerably. As the cross section of the wooden frame increases, it provides better insulation. The U-value of the wooden frame varies between 1.5 and 2.5 W/m^{2}K according to its design and section.[20] The sample of wooden frame section is shown in the Figure 2.3.

Figure 2.3. Wooden frame (Source: Wooden Windows, Carmave[26])

2.3.1.2. Aluminum Frames

The aluminum frame has more durable than wooden frame because of its resistance to external factors. These frames are highly preferred due to its easy to maintain and manufacture. However, the biggest disadvantage of the aluminum is the high thermal conductivity compared to the wood. It is not a good insulation material.

There are many air spaces inside the aluminum frame. Their effects on heat transfer rate are examined in detail with the studies in the window research area. And nowadays, the thermal performance of these frames is become comparable to the wooden frame because of applied to the thermal break systems to aluminum frame and using optimum air gaps and low emission surfaces in the frames.[27] As seen in the Figure 2.4 one of the section of the aluminum frame is shown.

Figure 2.4. Aluminum frame (Source: Proyapı[28])

2.3.1.3. PVC Frames

Vinyl material is a version of advanced synthetic plastic. It is also known as polyvinyl-chloride (PVC). This frame is easy to shape, resistant to impacts and durable. Thermal performance of this frame is as good as the thermal performance of wooden frames. Having a hollow structure is an advantage for improving thermal performance. These gaps can be filled with low conductivity materials as in the aluminum frames. Vinyl frames are also resistant to moisture.[20] For all these reasons, it is the most preferred type of frame in dwellings.

PVC has more thermal expansion coefficient than the wood and aluminum. This can be increased the ratio of deformation. The biggest disadvantage of vinyl is that no recyclable material is. The Figure 2.5 below is an example section of the vinyl frame.

Figure 2.5. PVC frame (Source: Pimapen[29])

2.3.1.4. Other Frames

Composite frames produced by combination of several materials are usually obtained by covering the outer surfaces of wood frame with aluminum or vinyl material. Steel frame has an advantage of durability compare to other frames, it is not preferred because of caring and manufacturing difficulties. There are also fiberglass frames which are similar with PVC frames. However, the fiberglass frame is more durable than PVC frames.

2.3.2. Glazing Systems

The glass which is one of the oldest artificial materials has many uses. It is used in many sectors such as construction, automotive, household appliances, pharmaceuticals, food, beverages, cosmetics, tourism, furniture, electricity, electronics and energy. For this reason, the glass sector is of great importance for the economies of the country and this sector grows at an average of 2-4% every year. World glass production is estimated to be around 120 million tons. In Turkey, the production capacity of glazing industry is 3.5 million tons. As shown in Figure 2.6, glass production distribution in European countries consists of 65% glass containers, 27% flat glass, 3% household glassware, 2% fiber glass and other glassware.[30] This means that thousands of tons of flat glass are produced every year for use in the building sector.

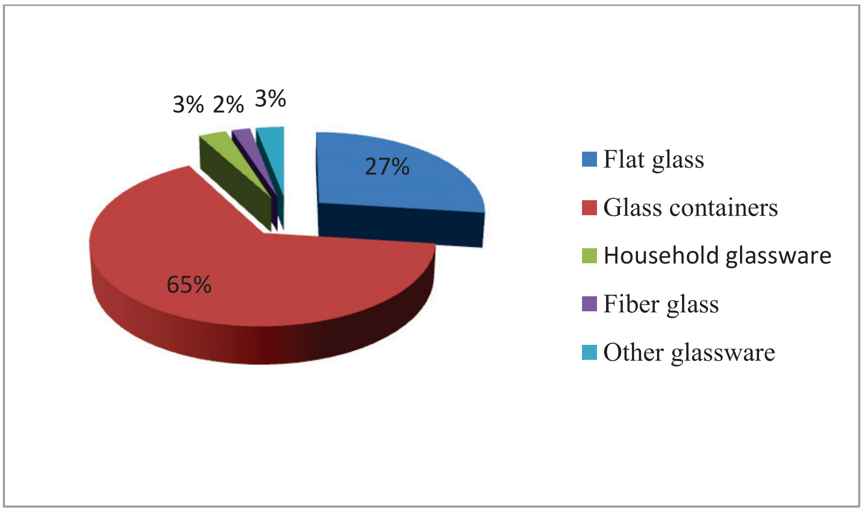


Figure 2.6. Glass production distribution of European Member countries (2012) (Source: [30] modified from the "Standing Committee of the European Glass Industries" website)

Multiple glazing systems consist of glass panes, spacers that determine the gap width and heavy infill gases which improve the thermal performance of the windows. The glazing systems have been developed with the technological growing and users requirements day by day. Now there are too many types of glazing systems which are examined in the following section of 2.5.

2.4. Glass Manufacturing

The glass is an inorganic product of fusion cooled in a solid state without crystallization. Various chemical substances can take the form of glass, among the inorganic ones are mainly; silicon (Si), boron (B), germanium (Ge), phosphor (P) and arsenic oxides (As). Generally, glass is a type of soda, lime and silica (sand). Soda-lime glasses are used in making all kinds of vessels, flat glasses, automobile glass and household glassware. Normal flat glass has ingredients of 71-75 percent silica sand, 12-16 percent soda, 10-15 percent limestone and small amounts of glass in other parts. Light permeability, thermal behavior, strength properties of the glass may vary depending on the amount of the components of glass.[31]

Glass production processes are as follows:

- Most of the silica-based raw materials are made suitable for melting.
- This mixture is then melted in the furnace by generator gas.
- After melting process, materials are cleaned and stocked.
- According to the type of glass to be obtained, these raw materials are blended in certain proportions.
- The mixture is melted by heating up to 1600°C in special furnaces.
- It is taken into the glass forming section which is melted according to the characteristics of the product.
- Then, it is formed with the methods of blowing, press, rolling, buoyancy, tossing and pouring.
- Glass is re-heated and cooled in a controlled manner and it becomes more durable. The later technology developed a sensor that detects the stress level of the glass.
- Finally, it is stored with special packaging and storage equipment and ready for transportation.[32]

According to the classified main production areas, as can be seen in the Figure 2.6, the glass material of flat glass has the importance in the architecture and energy sector. After these processes of manufacturing, architectural glass products have secondary process such as coating, laminating, silvering etc. And in recent years, this type of flat glass is produced by the float glass technology.

2.4.1. Float Glass Technology

Float Glass is commonly known as window glass. The float process is developed by the Alastair Pilkington in 1952. In Turkey, the production of modern float glass has started with the company of Düzcam Şişecam A.Ş. by taking a facility in 1981. In 1997, this company completely stopped the old technology of glass production which is "Sheet technology" and started to make all investments through the float method. And the company has become the 1st company in Europe and the 5th company in the world with its production capacity.[33]

With this production method, it is possible to make the glass thickness from 0.4mm to 25mm and in widths up to 3 meters. Presently, float glass production is approximately 90 percent of the production of flat glass in the world because of its advantages such as minimum production loss, requirement of minimum labor and ease of glass coating process. In the float glass process, molten glass at approximately 1000°C is poured onto a float bath of molten tin and it floats on the tin. It becomes a surface and leaves the bath at 600°C. Coatings that make changes in the optical properties of glass can be applied to the cooling ribbon of glass. Then the glass is cooled to the room temperature to prevent buildup of stress. Finally, it is cut, packed and stored.[34] Figure 2.7 shows the process:

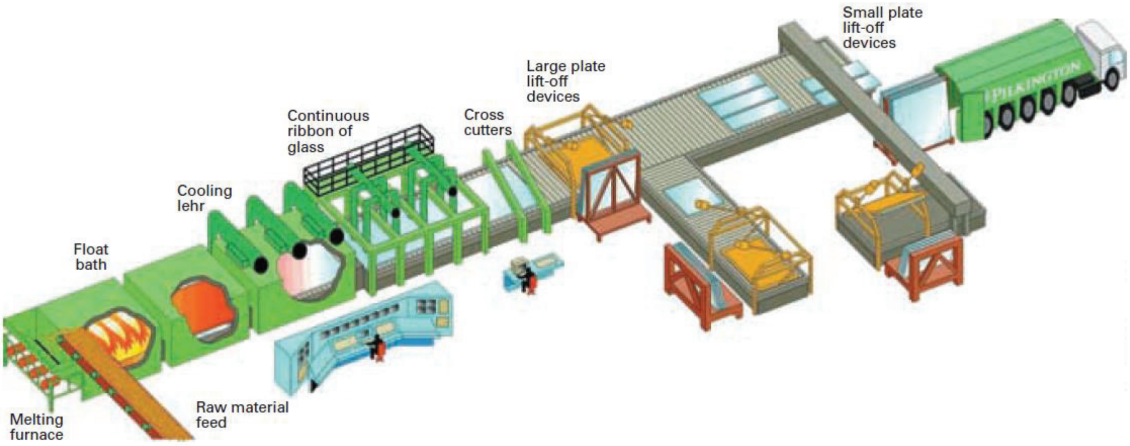


Figure 2.7. Clear float glass production process
(Source: NSG Group[34])

2.5. Types of Glass

According to the properties and characteristics glasses have large variety. But, architectural glass types can be examined in six main categories which are thermal insulation glass, solar control glass, fire protection glazing, glass for solar energy, noise control glazing, safety and security glazing.

2.5.1. Thermal Insulation Glass

Using insulating glass (IGU) instead of standard glass can reduce the heat losses from window by up to 80%. Insulating glasses are usually make up of two or more glazing units by combining with a spacer and sealant. The spacer can made up with the aluminum, composite plastics etc. And the edge seal is produced as binary. Because it protects the cavity between the glasses from outside mechanical effects and also protects the moisture.[5] The glazing units are generally combined under factory conditions. And these glasses contain dry air or heavy inert gases in the gap between the panes. The following Figure 2.8 shows details of the insulating glass described as a double glazing window.

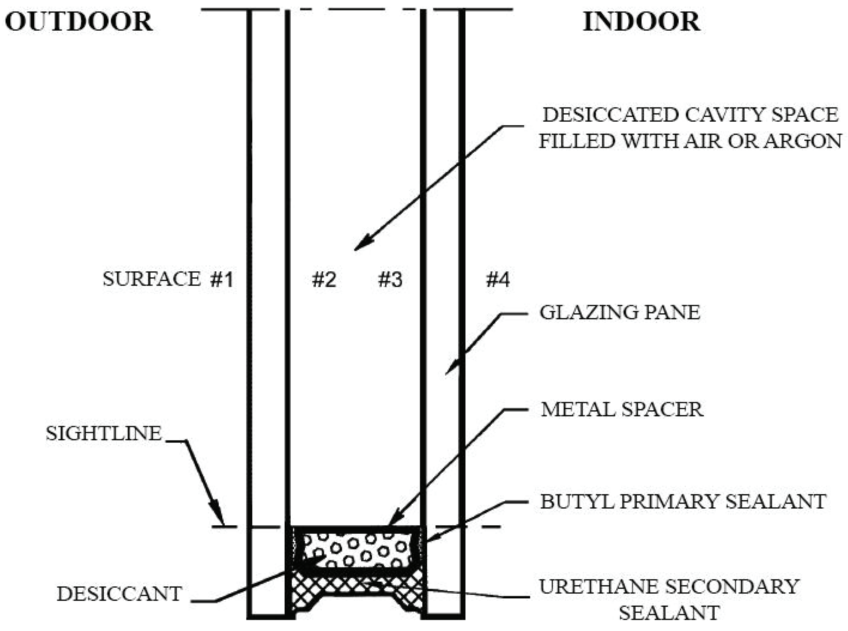


Figure 2.8. Thermal insulation double glazing window construction detail (Source: ASHRAE[15])

2.5.1.1. The Filling Gases

The cavity between window panes of the thermal insulating glass is usually filled with air which is subsequently desiccant dried. Because dry air is an easily accessible material for using between panes. But in the cavity, it can be used a gas having a lower thermal conductivity which are argon (Ar), krypton (Cr) and xenon (Xe) to reduce energy transfer instead of air. These viscous, slow-moving gases minimize the convective heat transfer coefficient efficiently. Dry air is the most widely used for infill gas from the manufacturers. And argon is more preferred since it is both cheaper and easier to find than krypton and xenon. Less than 1% of the Earth's atmosphere involves argon gas. Besides, argon is non-toxic, inert and clear gas. And also, its thermal conductivity is approximately 67% that of air.[20] Table 2.1 shows the thermal conductivity of these heavy inert gases.

Table 2.1. Thermal conductivities of the inert gases.[35]

Gases	Conductivity
Air	0.026
Argon	0.018
Krypton	0.009
Xenon	0.005

2.5.1.2. Number of Glazing Units

The single-glazed window is no longer preferred in new constructed building. Besides multiple-pane windows have many benefits such as condensation prevention, sunlight control and sound insulation, the most important feature of the multiple-pane windows is providing very well thermal insulation. Although it increases the cross section of glass, double and triple glazed windows have become a preferred type for the construction sector since they reduce the amount of heat transfer rate. And quadruple pane windows are not used much because of high cost and difficulty of use.

2.5.1.3. Low-e Glass

Low emissivity coating glasses have very low permeability and high reflectance to long IR wavelengths. They reduce the amount of heat transfer significantly because of preventing the radiation heat transfer substantially. In particular, the coatings, applied to the inner surface of the inner glass in the double glazing windows, reflect the heat moving back into the interior space. This coating should be applied on the inner surfaces for the multiple glazed windows. In case of contact with external environment may be damaged it.[5]

These windows do not have daylight blocking features while providing heat control. For this reason low-e glass has an important role in protecting the inside from overheating in summer, from heat losses in winter time as well as allowing the light to enter the interior space. The Figure 2.9 is shown an example of a low-e glass.

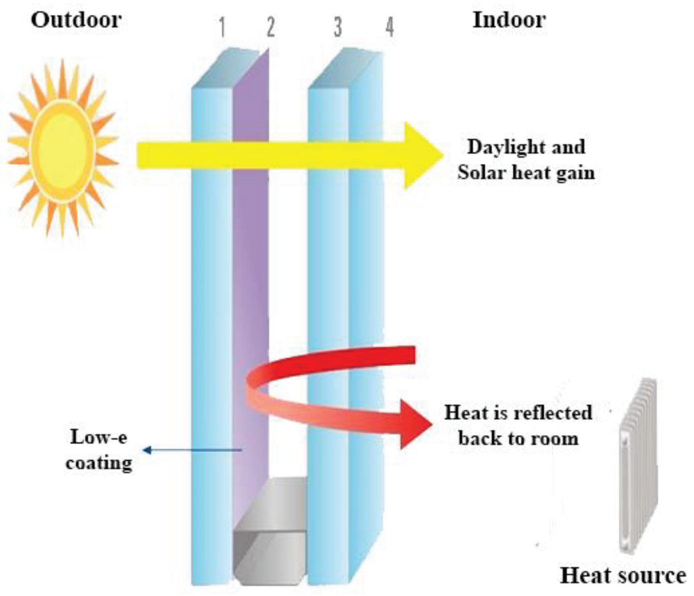


Figure 2.9. Low-e coating on double glazing window unit
(Source: Şişecam Düzcam[33])

2.5.2. Solar Control Glass

Solar control glasses are used for reducing the negative effects of solar energy on the indoor such as overheating and glare problems. It is preferred usually used in daytime office buildings.

2.5.2.1. Solar Low-e – Spectrally Selective Glass

Solar low-e glass is especially advantageous to use in warm climates. It is a type of glass that prevents the heat loss in winter time and reduces the heat gain in summer time. It provides only visible spectrum of sunlight to pass, reflects the infrared radiation. So, it has high visible transmittance ratio (VT) but low solar heat gain coefficient (SHGC). Double glazing solar low-e glass is better than the double glazing produced by standard glass 14% for heat protection, 42% for solar control.[5]

With the developing technology, the emissivity values of the coatings can be reduced to 0.02. It is usually added to the inner surfaces of multiple glazed windows. However, it is not recommended to add middle glass of the triple pane windows. Because it can cause overheating and breaking the glass unit.[12] Representative solar low-e glass is given in Figure 2.10.

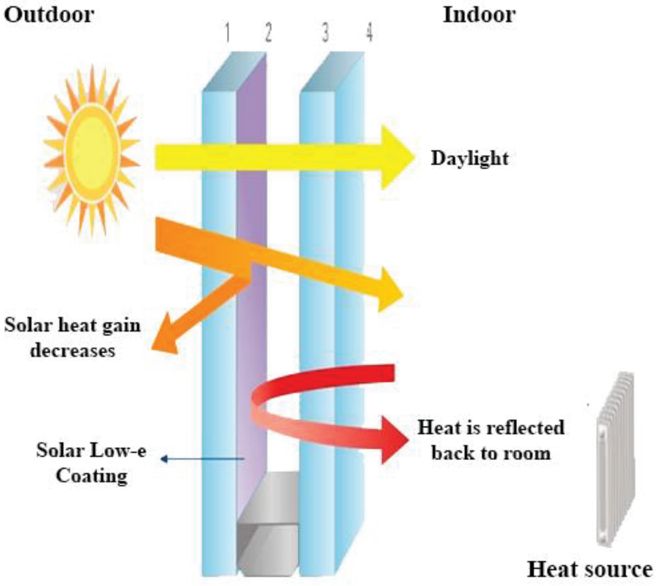


Figure 2.10. Solar Low-e coating on double glazing window unit (Source: Şişecam Düzcam [33])

2.5.2.2. Tinted Glass

Tinted glasses are obtained by adding metal oxide material to the glass. Glass color changes according to type of metal used. They are usually produced in blue, green, smoked and bronze colors. According to the color of the glass, the properties of the light transmittance, solar heat gain coefficient and reflectivity of the glass are changed.[20]

Tinted glasses provide privacy because they do not show inside from outside and provide visual connection with the outside environment as well. They prevent excessive sunlight and glare. The biggest disadvantage is that it prevents the natural lighting because of blocking the sun light.

2.5.2.3. Reflective Coated Glass

Reflective coated glass has high coefficient of reflection of sunlight. Therefore, they are evaluated in the solar control glass category. They are mainly used in office buildings. These coatings can be applied to tinted or float glass. There are many options in metallic colors such as silver, gold and bronze. These color variations also change the other physical properties of the glass. When using reflective coated glass on the facade, necessity for artificial lighting is increased inside. Because, these glasses have very low daylight permeability. The solar heat gain value is 50% less than a standard glass.

2.5.3. Fire Protection Glass

Fire protection glass is a technological glass that is protected against flames and smoke. There are different types of glasses according to their performance levels. These glasses also protect themselves from the temperature of the fire. It is mostly used in commercial buildings such as schools, hospitals etc. Transparency of these glasses is an ongoing working area.[34]

2.5.4. Glass for Solar Energy

Solar panels are generally designed for use on roof of houses. These photovoltaic glass panels that generate electricity by solar energy promote the use of renewable resources. These glass panels have started to design to be used in building facades currently. These glasses are designed as transparent solar panels and are called also “Solar Windows”. It has been implemented and produced by many innovative companies. These solar glasses have also thermal insulation characteristics to minimize the energy requirement for heating and cooling.[36]

2.5.5. Noise Control Glass

In glass systems, noise control has become a necessity. Especially in areas with traffic density, in office buildings, in the airports the acoustic performance of the glass should be good enough. It is generally obtained by adding polyvinyl butyral material (PVB) between the laminated glasses. In addition to providing sound insulation, it can also be used for security purposes. It may combine with other types of glass such as insulating glass, solar control glass etc. These glasses are of great importance for user comfort needs.[34]

2.5.6. Safety and Security Glasses

Safety and security glasses are highly resistant to external effects and weather resistance. These glasses are two types according to production methods such as tempered glass and laminated glass.

2.5.6.1. Tempered Glass

Tempered glass is also known as toughened glass. When the glass is heated to approximately 650 degrees, it is cooled rapidly with air jets. Thus, the core is allowed to cool to room temperature while the surface of the glass has cooled. The tension in the core allows the glass to be dispersed into smaller and safer glass particles when the glass breaks. It can therefore be used for security purposes.[34]

2.5.6.2. Laminated Glass

Laminated glass is formed by bonding the two glass sheets with a polymer film layer. Air bubbles inside the glass are eliminated with the help of heat and pressure. Thus, it appears as a single glass. Even if broken, pieces of glass can be held together and so that it can be used as a security glass.[34]

2.6. Thermal Performance of Window Glass

Thermal performance is the main issue of multiple-glazed window. U value determines the thermal performance of the windows which are directly connected to the external environment. The lower the U value of the windows means the less heat is transferred from the window and the more the heat is protected. Heat transfer takes place from a high temperature environment to a low temperature environment. So, it is caused by the temperature difference. And it occurs in three different modes: conduction, convection and radiation. While the heat transfer from the window glass surface is carried out by conduction and radiation, it is carried out by conduction, convection and radiation from the gas filled cavity between the window glazing units.

2.6.1. Heat Conduction

Definition of the heat conduction "is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles".[37] Conduction can take place in all phase of the substance which are solid, liquid and gases. It is calculated as follows:

$$\dot{Q}_{cond} = kA\frac{T_1 - T_2}{\Delta_x} = -kA\frac{\Delta T}{\Delta x} \quad (W) \tag{2.5}$$

where the constant of k is the thermal conductivity of the material. It defined as how much heat is transferred through a unit thickness of the material per unit area per unit temperature difference. A low value for thermal conductivity indicates that the material is an insulator material. Thermal conductivity, k, can vary with temperature, but in conduction analysis k is assumed as a constant at the average temperature in general. Each material has different heat storage capacity. Both the specific heat, c_p, and the heat capacity, ρc_p, represent material's ability to store thermal energy. And thermal diffusivity, α, represents how quickly heat diffuses into a material and it is the combination of these factors:

$$\alpha = \frac{Heat\ conducted}{Heat\ stored} = \frac{k}{\rho c_p} \quad \left(\frac{m^2}{s}\right) \tag{2.6}$$

The heat flux, q, is the rate of heat transfer through a given unit surface perpendicular to the heat transfer direction, per unit time. It can be described heat transfer rate per unit area, basically and express as:

$$q = k\frac{T_1 - T_2}{L} = k\frac{\Delta T}{L} \qquad \left(\frac{W}{m^2}\right) \tag{2.7}$$

2.6.2. Heat Convection

Heat convection “is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion”.[37] Convection heat transfer rate depends on mainly fluid velocity and fluid properties. And fluid properties may change according to temperature. Convection heat transfer rate can be calculated by “Newton’s law of cooling” as:

$$\dot{Q}_{conv} = \; hA_s(T_s - T_\infty) \qquad (W) \tag{2.8}$$

where h is the convection heat transfer coefficient in W/m^2°C, A_s is the surface area, T_s is the surface temperature and T_∞ is the fluid temperature far from the surface. The convection heat transfer coefficient value, h, can change depends on the variables that influencing convection such as fluid properties, fluid motion, surface geometry and the bulk fluid velocity.

There are three types of convection; natural convection, boiling convection and forced convection. Forced convection occurs when the fluid is forced by external effects such as a fan, pump or the wind. But in this thesis, natural convection will be examined.

Natural convection occurs when fluid motion is caused by the buoyancy forces due to the density differences. Since there is no velocity resulting from an external effect, the density difference is caused by temperature gradient of the fluid. In this study, natural convection occurs by the temperature difference and the body force of the gravity in the filling gas cavity between window panes. Heat transfer inside cavity is complicated because the fluid does not remain steady in general. In vertical cavities, as in this study, the fluid adjacent to the hot surface rises and the fluid adjacent to the cold surface fall. Thus the heat transfer rate increases in the cavity.[38]

While the buoyancy force is getting larger, the natural convection becomes stronger and the heat transfer rate becomes higher. The Figure 2.11 shows the effect of the natural convection on the heat transfer rate and the fluid motion in the air filled cavity:

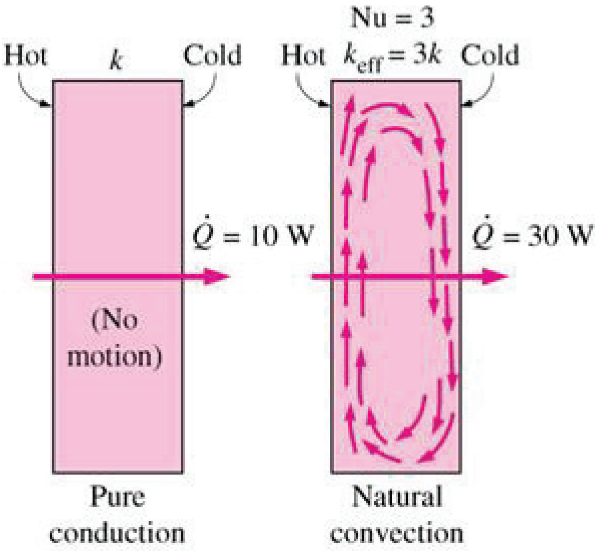


Figure 2.11. Heat transfer throgh the enclosure by natural convection is three times that by pure conduction. (Source: Çengel[38])

If the heat transfer takes place only by pure conduction, Nusselt number (Nu) equals 1 as shown in the figure above. The increase of Nusselt number indicates that the natural convection is also increased. The correlation of Nu is generally calculated as:

$$Nu = \frac{hL}{k} \tag{2.9}$$

with the increasing of buoyancy force effect on the fluid, the fluid motion becomes turbulent. When Ra>1708 the hexagonal cells is observed in the flow and for Ra > 3×10^5 the turbulent flow occurs. The Rayleigh number for the cavity expressed as:

$$Ra = \frac{g\beta(T_1 - T_2)L_c^3}{\vartheta^2}\mathrm{Pr} \tag{2.10}$$

where T_1 and T_2 are the temperatures of the panes' surfaces and L_c is the distance between window panes. The other properties of the fluid are determined according to the average temperature of the fluid which is $T_{avg} = (T_1 + T_2)/2$.

In order to improve the thermal performance of the glass systems, the cavity between panes is filled with a low thermal conductivity gas to reduce heat transfer by conduction and convection. So, the spacing width and the heavy infill gases' properties are significant factor that affects the heat transfer rate.

2.6.3. Thermal Radiation

Thermal radiation is the third mechanism of heat transfer. Radiation heat transfer can occurs in every phase of material such that in solids, in liquids and in gases. Also, radiation transfer occurs in a vacuum different from the other heat transfer mechanisms.

Thermal radiation is emitted as a result of energy transitions of molecules, atoms, and electrons of a substance. One of the radiation properties is the emissivity value of a surface. It is the ratio of the radiation emitted by the surface to the radiation emitted by a blackbody in same conditions. A blackbody emits the radiation in every direction. It is defined as a perfect emitter per unit time and per unit area. And emissivity value (Ɛ) of the blackbody is 1.[24]

For the multiple pane windows, the radiation mechanism must be considered. Especially in the filled gas of the double pane windows, radiation heat transfer is about half of the heat transfer rate. The total heat transfer rate is specified as:

$$\dot{Q}_{total} = \dot{Q}_{conv} + \dot{Q}_{rad} \tag{2.11}$$

With the properly selected windows, it is able to prevent heat loss by radiation heat transfer. Especially, in cold regions, the windows should have the low emissivity (high infrared reflectivity) properties inside. In warm regions, the windows should design to reduce solar heat gain while designing allow the daylight. It can be provide with a coated low-e film inside and reflective film outside. The precautions for the radiation heat transfer through windows as shown in Figure 2.12.

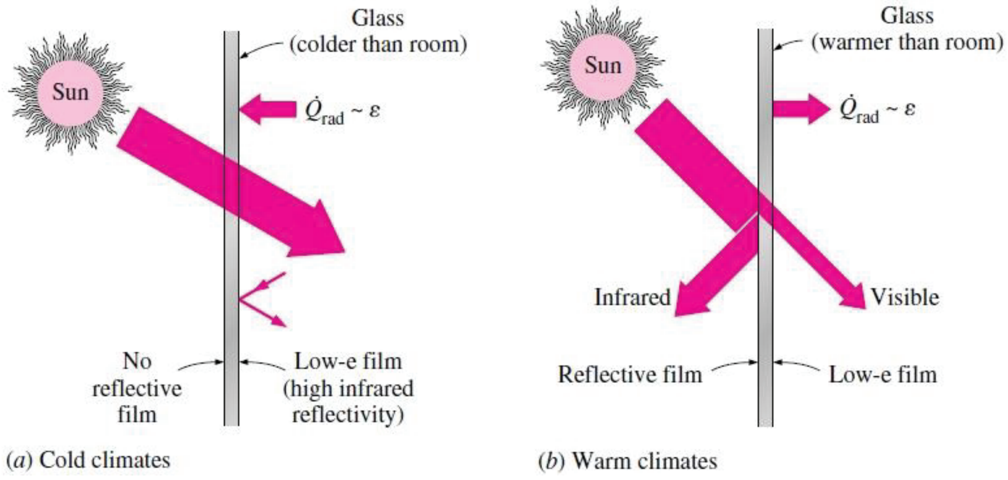


Figure 2.12. Radiation heat transfer between a room and its windows (Source: Çengel [24])

The emissivity of the glass surface, ε, has significant impact on radiation heat transfer rate. And, radiation heat transfer through window panes can be expressed as:

$$\dot{Q}_{rad} = \varepsilon_{effective}\sigma A_s(T_s^4 - T_2^4) = \frac{\pi A_s(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \quad (W) \qquad (2.12)$$

where ε is the emissivity of the glass surface, A_s is the surface area, σ=5.67x10^{-8} W/m^{2}K^4 is the Stefan-Boltzmann constant, T_1 and T_2 are the surface temperature of the glass panes and ε_1 and ε_2 are the emissivity values of the panes. $\varepsilon_{effective}$ is the effective emissivity calculated as [38]:

$$\varepsilon_{effective} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad (2.13)$$

The ordinary glass emissivity is 0.84. According to this calculation, the effective emissivity of the ordinary glass equals to 0.72. This means using a coating low emissivity material on the glass surface reduces the radiation heat transfer rate noticable.

2.7. Previous Studies about the Thermal Performance of Glazing Systems

Aydın[39] conducted an analysis to determine the thickness of the optimum air layer between double glazing. For this purpose, four cities were selected which have different climatic conditions in Turkey (Ankara, Antalya, Trabzon and Kars). Winter design temperatures for these considered cities were defined as constant temperature on the outer surface of the glass as a boundary condition. Heat transfer through the double glazed window by natural convection mechanism was simulated using a computer code which uses “finite difference” technique. According to these results, optimum values differed from city to city. These values were found to be 18-21 mm for Antalya, 15-18 mm for Trabzon and Ankara and 12-15 mm for Kars. It was expressed that in these cities, if the windows are changed according to these optimum values instead of using 9 mm gap width, the energy saving to be provided was 40% for Antalya, 34% for Trabzon, 29% for Ankara and 21% for Kars.

Another study of the Aydın[40] was to about heat transfer through double glazed windows again. It was to determine the optimum air layer thickness between the double glazing for regions with different climates in Turkey which as the four cities of Ankara, Antalya, Kars and Trabzon. Heat transfer through double glazed windows was numerically examined by using “Finite difference” technique. In this study, in addition to the previous study of the same author[39], the interaction between the conduction heat transfer in the glass surfaces and the convection heat transfer in the cavity was also investigated. Two different thermal boundary conditions were defined. In the first case, a constant temperature was defined on the outer surface of the inner and outer glass according to the average temperature data in the cities. In the second case, convection boundary condition was defined for the outer surfaces of the glass pane. Heat transfer was reduced in the first case as the convection resistance of the inner and outer air was not taken into account. As a result, the optimum air layer thickness between the double glazings varies according to the cities. These results are similar to study[39] of first mentioned, since heat transfer was reduced as only conduction on the glass was calculated. Although this study has a more realistic approach that the previous work of the author, it can be generalized as it does not change the optimum value of the U value. Depending on the force of the wind, it has also been shown that the variation of the forced heat transfer coefficient for the outer surface has no significant effect on heat transfer.

In the study of Weir G. and Muneer T.[41], Life Cycle Analysis (LCA) of double glazed windows was performed. For this purpose, four main materials, infill gas, timber, aluminum and glass, which are used in window production, were investigated due to embodied energy, production processes and environmental effects. The use of argon, krypton and xenon gases in the cavity between the window panes was compared with using air. As the molecular weight of gases increases, its thermal conductivity decreases. Thus, high performance windows can be produced without increasing the weight of the frame structure and the gap width. However in the study the airborne percentages of these gases and the energy consumed during the segregation process from air were also taken into account. As a result of the research, argon filled windows were found to contain the least amount of combined energy because of the high percentage of air. And it was expressed again produced very little greenhouse gas with argon uses. Although having more than 0.01 MJ of energy compared to air, argon filled window were also found to be less heat transfer amount because of the lower U value.[41]

The energy efficiency of the window was analyzed through single, double and triple glazing windows in this study.[10] The flow and heat transfer problem were calculated with the CFD method. The calculations were carried out different glazing gap width and at different outdoor temperatures. To understand the importance of heat transfer by radiation, it was added and removed from the calculations respectively. It has been observed that the increase in the number of glass decreases the radiation and slows down the flow in the cavity so suppresses the convection heat transfer. Thus, the amount of heat transfer also decreased. The increase in the temperature difference increased the amount of heat transfer. For this reason, it has been shown that by increasing the number of glass panes from 2 to 3 and from 3 to 4, energy savings can be achieved about 50% and 33% respectively. The order of importance for all parameters as a result of the study; the number of glass, the emissivity of the surface and the gap widths.[10]

In another study the heat transfer for the double and triple glazing windows which have different air layer thicknesses was investigated.[9] This study also was carried out with the help of CFD method. It was observed that a change in the amount of heat transfer by varying the outdoor temperatures. The result was using triple glazed windows instead of double glazed windows reduced the heat transfer about 50%. By reducing the emissivity of the glass surfaces, total heat losses have decreased significantly. And it was determined the radiation heat transfer rate is more dominant than the conduction and convection heat transfer rates.[9]

The authors[14] presented an analysis for the calculation of the effect of the flow patterns on heat transfer in vertical geometries. CFD simulations are made with different gap widths, different heights and various temperature differences. The obtained results were compared with the experimental, analytical and numerical studies performed in the past. Thus, the analysis was confirmed and the deficiencies in the literature data were shown. Simulations were consistent with literature data[42] in the range of 16 ≤ Aspect Ratio ≤ 40, and 3.55E+03 ≤ Ra ≤ 2E+04. The deviation of the obtained Nu values is in the range of ±10%. Correlations that can be used to accurately determine the heat losses in the air filled vertical cavity are proposed. This is important because the effect of height is taken into account in generalized correlations.[14]

The authors[43] numerically investigated laminar natural convection in a closed three-dimensional air filled cavity. As a result of both two-dimensional and three-dimensional analysis, they have shown that obtained Nusselt numbers were the same both these analysis for the large horizontal aspect ratios.[43] In another study showed that two-dimensional analysis was sufficient in the heat transfer analysis through window, the effect of W/L (horizontal aspect ratio) was investigated. When in the three-dimensional vertical cavity the horizontal aspect ratio is greater than 5, two-dimensional analysis can be conducted. Because there were no significant change in the results.[44]

In line with these recent studies, the aim of this thesis is improving the thermal performance of triple glazed windows' glazing part. To determine proper window for the average winter design temperatures of different cities of Turkey, various affecting parameters were investigated. Four different scenarios of gap widths were determined as 12-12 mm, 16-16 mm, 12-16 mm and 16-12 mm. These combinations of gap widths have not been tried in previous studies before. With this study, optimum window configuration can be selected with a lighter frame and less filling gas according to different outdoor temperatures.

CHAPTER 3

MATERIAL AND METHOD

3.1. Computational Fluid Dynamics (CFD)

The use of Computational Fluid Dynamics (CFD) modeling is well documented in window research areas. For understanding flow effects on the heat transfer through windows, analytical solutions are not enough. So the numerical simulations and experiments are essential in this area. And also, CFD analysis reduces the total effort and cost required for testing and data collection. Although CFD method is portable, easy to use and modify compared to the experiment, it does not replace the experiment.

CFD is the science of estimating fluid flow, heat and mass transfer problems, chemical reactions and other related areas. For this estimation, CFD calculates the momentum, energy and governing equations. It can provide detailed information about fluid flow. Distribution of pressure, velocity and temperature of fluid flow can be analyzed by this method.[45]

ANSYS CFD solvers are based on the finite volume method. The domain is divided into a finite number of control volumes. The points that provide the connection between the volumes are called "nodes" or "cells". And Navier-Stokes equations which define fluid motion are assumed at all these nodes. They are solved by a finite number of equations. The creation and number of nodes depends on the numerical solution methods and flow types. For two-dimensional (2D) domains, the cells mean areas, for three-dimensional (3D) domains the cells mean volumes.

CFD solutions consist of three main stages; preprocessing, processing/solver and post-processing. In preprocessing part, the flow field and the geometry are modeled and the grid system is determined. The quality of a CFD analysis depends on the quality of the grid. Then, fluid properties are identified and boundary conditions are applied on the edges of the computational domain for 2D analysis. It is important to define appropriate boundary conditions for the accuracy of the CFD solution. In processing part, the momentum, energy and the other equations are solved. At the end, in post-processing part, the graphical plots or reports of the variables are analyzed.[45]

Some research areas that use the CFD method are:

- Aerodynamics of cars and aircrafts,
- Numerical weather prediction,
- Heat and mass transfer,
- Hydrodynamics of ships,
- Chemical, fuel gas sectors,
- Acoustics and fluid-structure interaction,
- Nuclear reactor design,
- Design of interior and exterior of buildings,
- Blood flow analysis in biomedical engineering.

3.2. Fluent

Fluent is computational fluid dynamics software that uses finite volume methods. It is the most widely used software in the CFD sector. It can be used also in the heat transfer problems. Thanks to its easy use, fluent can perform performance analysis even at the design stage of product. Thus, the improvement conditions for the products are provided before offering to the market. ANSYS FLUENT software contains the broad physical modeling capabilities such as turbulence, laminar flows, heat transfer problems, problems involving chemical reactions, acoustic and multi-phase flow problems.[23]

The steps of solving engineering problems using ANSYS FLUENT; pre-analysis, geometry, mesh, physical setup, numerical solution, verification and validation.

In Fluent, there are two numerical methods; pressure-based solver and density based solver. The main difference between two solvers is the way of approaching energy and momentum equations. The pressure based solver was formulated to solve low-speed incompressible flow, while the density based solver was formulated to solve high-speed compressible flows originally. However, both methods have wide range of flow conditions recently.[46] Fluent solves the integral equations by both methods for conservation of mass and momentum and energy. The discretization processes are similar for each of them, but the approaches are different.

3.3. CFD Simulations

The computations simulate the heat transfer by natural convection and radiation across a closed cavity between window panes.

3.3.1. Geometry and Boundary Conditions

The model that used in the study is shown in Figure 3.1. The glazing units were used as 4 mm thickness (*t*). Height (*H*) of the window is assumed to be 1 m as a constant. It is the most commonly preferred window size in the literature. Because of the horizontal aspect ratio of the window is very large, the flow is considered to be two-dimensional as reported in the references numbered.[43,44] So, the width (*W*) of the glass is not determined as a parameter. Convective boundary conditions are determined on the inner and outer surfaces of the glass. Besides, adiabatic boundary conditions are employed on the bottom and top surfaces and no-slip velocity boundary conditions are applied all surfaces (#2 to 5) in which air is contacted. L_1 and L_2 are thickness of the cavities that are changed according to determined scenarios.

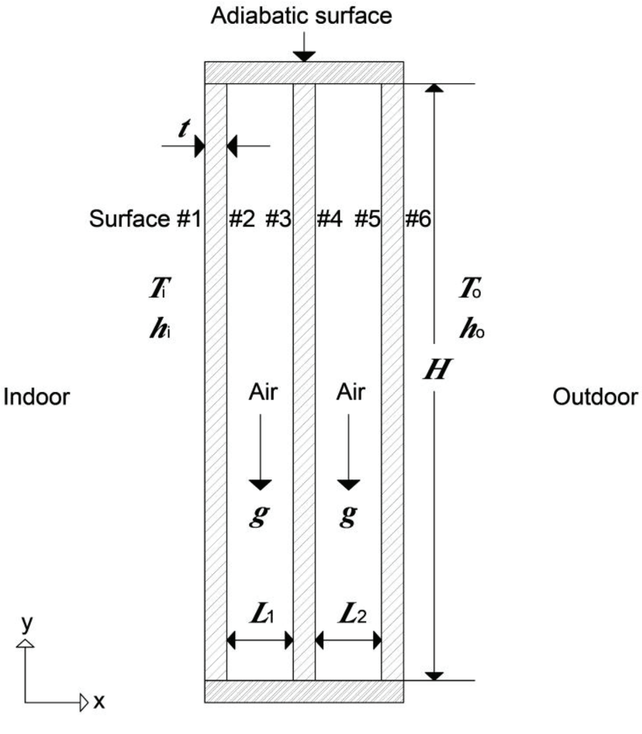


Figure 3.1. Schematic illustrations of the triple pane windows

Dry air was used in the cavities at 1 atm. The density (ρ) of air is calculated with the ideal gas law. The specific heat (c_p), viscosity (μ) and thermal conductivity (k) of air are assumed to constant and are determined according to average temperature of the analyzed model. Molecular weight of the air is assumed to be 28.966 kg/kgmol. Indoor temperature (T_i) is assumed to be constant and is taken 20 ˚C. Thus, the properties of air are changed according to outdoor temperature (T_o). Outdoor temperatures are specified considering the heating design data of Turkey which are investigated in the study as referenced.[47] The Table 3.1 shows the winter design temperature of the different cities of Turkey used in this study. The heating design temperatures are the 99.6% design dry-bulb temperatures for these cities. Table 3.2 shows also the thermophysical properties of air according to these temperatures.

Table 3.1. Heating design temperatures for the cities used in this study (T_o).[47]

City	Heating design temperature (°C)
Ağrı	-28
Sivas	-17
Amasya	-6
İskenderun	+5

Table 3.2. Temperature-dependent thermophysical properties for air for simulation parameters.[48]

City	T_{avg} (°C)	k (W/mK)	c_p (J/kgK)	v (m^2/s)
Ağrı	- 4	0.02334	1006	1.71E-05
Sivas	+ 1.5	0.02379	1006	1.74E-05
Amasya	+ 7	0.02416	1006	1.76E-05
İskenderun	+ 12.5	0.02458	1007	1.79E-05

The properties of the glazing unit are initially defined according to the standard glass. Emissivity (ε) of glass is 0.84, thermal conductivity (k) of glass is 0.92 W/mK, glass density (ρ) is 2530 kg/m^3 and the specific heat (c_p) is 840 J/kg.K.[15] The heat transfer coefficient of the inner surface, h_i, is taken to be 8.29 W/m^{2}K and the heat transfer coefficient of the exterior surface, h_o, is taken to be 34 W/m^{2}K.[38] The air space surface coefficient (h_s) of the window is not a property of the fluid. It will be determined as a parameter of the analysis. It depends on temperature difference, the wide of cavity, the surface emissivity of the panes, fluid properties and fluid motions and so after running the code, (h_s) is obtained from:

$$h_s = \frac{Nu\,k}{L} \qquad (\frac{W}{m^2K}) \tag{3.1}$$

and the heat flux, q, is described as heat transfer rate per unit area, which means that (h_s) can be calculated as:

$$h_s = \frac{q}{\Delta T} \qquad (\frac{W}{m^2K}) \tag{3.2}$$

The overall heat transfer coefficient (U-value) for multiple pane windows is calculated used with space surface coefficient (h_s), the heat transfer coefficient of the inner surface, h_i, the heat transfer coefficient of the exterior surface, h_o, and thermal conductivity (k) of glass. And U-value of triple pane window center region which is the aimed parameter is calculated with this equation [38]:

$$\frac{1}{U_{(Center\ region)}} = \frac{1}{h_i} + \frac{1}{h_{s1}} + \frac{1}{h_{s2}} + \frac{1}{h_o} + 3\,\frac{L}{k_{glass}} \tag{3.3}$$

where $h_s = h_{rad} + h_{conv}$ is the combined radiation and convection heat transfer coefficient. For reducing U-value of the window, h_s should be reduced also. It can be achieved with the minimizing the radiation heat transfer by coating the glass panes with low-emissivity (low-e) coating material. The emissivity value of the glass can be decreased as minimum 0.04 with using low-e coating. [49] So, for this study five different emissivity values are identified on surfaces which are 0.1, 0.25, 0.50, 0.75 and standard value of 0.84. And various combinations with these coatings have been tried. It has been investigated which glass surface and which temperature range is more effective while reducing heat transfer rate.

Another parameter affecting the heat transfer rate is the gap widths between the glass panes. Four different gap widths are considered in this study which is expressed as L_1 and L_2 in the model as shown in Figure 3.1. L_1 and L_2 are specified as 12 – 12 mm, 16 – 16 mm, 12 – 16 mm and 16 – 12 mm respectively. 12 mm and 16 mm are the most preferred gap width in the window sector. But in the literature, there were no analyzing about the combination of these two widths in one glazing unit. In this way, it may be possible to reduce the cross-section thickness in the production of glass instead using of two 16mm wide cavities in the windows.

In addition to these, when the gap width exceeds 16 mm, the air movement in the cavity increases. So the natural convection heat transfer also increases. Although the gas layer serves as a thermal insulation layer for conduction, there is no significant reduction in the U value in the wider gap width because of the convection heat transfer. It has been shown in previous studies.[14,10] Another negative effect of wider gap is increasing cross-section thickness of the glass. Thus the most preferred 12 mm and 16 mm wide gap are used in this study.

3.3.2. Grid Sizing and Sensitivity

Numerical calculations are performed for five different mesh structures for each gap width of cavity. The number of element size is defined between 0.125 mm and 1 mm for a gap. The number of grid nodes of the 12 mm wide cavity is; 24000, 48000, 96000, 192000 and 384000 and for the 16 mm wide cavity is; 16000, 32000, 64000, 128000 and 256000 respectively. As a result of the computations, 96000 found to be optimum number of grid nodes for the 12 mm wide cavity and 128000 also found to be optimum number of grid nodes for the 16 mm wide cavity. Grid numbers are determined considering computational time and accuracy. So, the mesh independency is provided for this study.

Computations presented that there are no significant changes in the heat transfer coefficient with finer grids. The results of the grid dependency study are plotted in the Figure 3.2 and Figure 3.3 below. The plotted graphics show the variation of the heat transfer coefficient of the cavity which is cold side of the window for both cavity widths which are 16 mm and 12 mm.

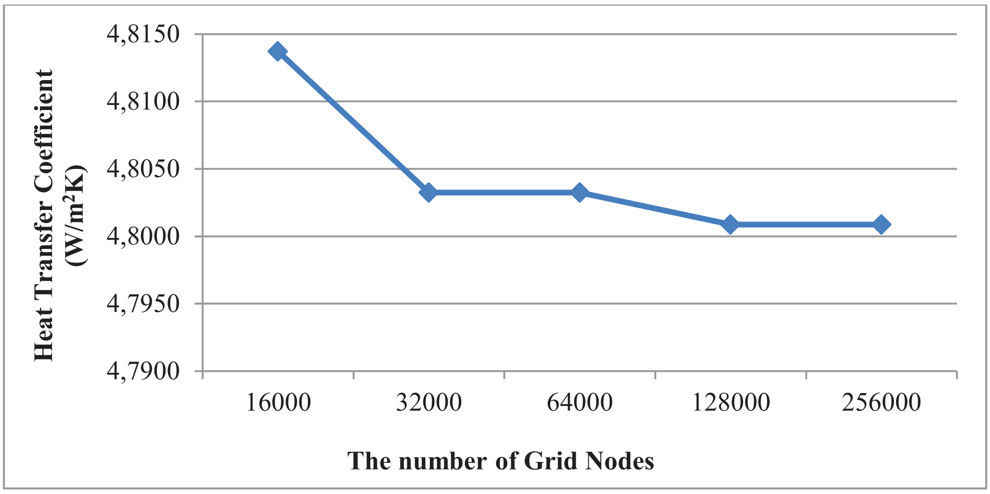


Figure 3.2. Heat transfer coefficient of the cavity in the cold side (*L*=16mm)

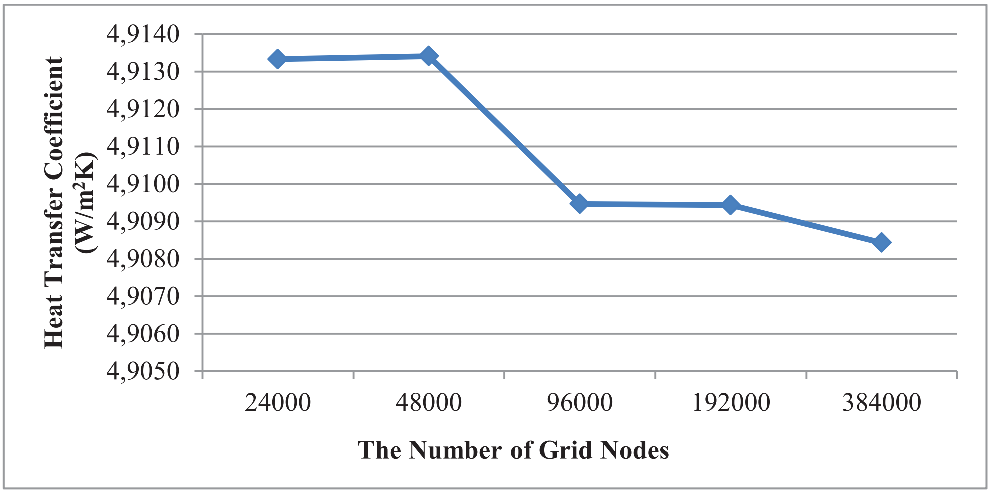


Figure 3.3. Heat transfer coefficient of the cavity in the cold side (*L*=12mm)

At the end of the calculations with different mesh structures, the element size of the both case is defined as 0.25 mm for the x-direction and 0.5 mm for the y-direction of the cavities. These determined mesh structures are used in the main calculations. So, mesh independency analysis minimized doubts about the accuracy of the numerical results. The physical model section of the mesh structures created for both gap widths are represented in the Figure 3.4. There is no inflation layer on the solid surfaces. Because the glass layer has no significant impact on the heat transfer analysis. The element size of the grid is 0.5 mm for both directions in these layers as can be seen in the figure below.

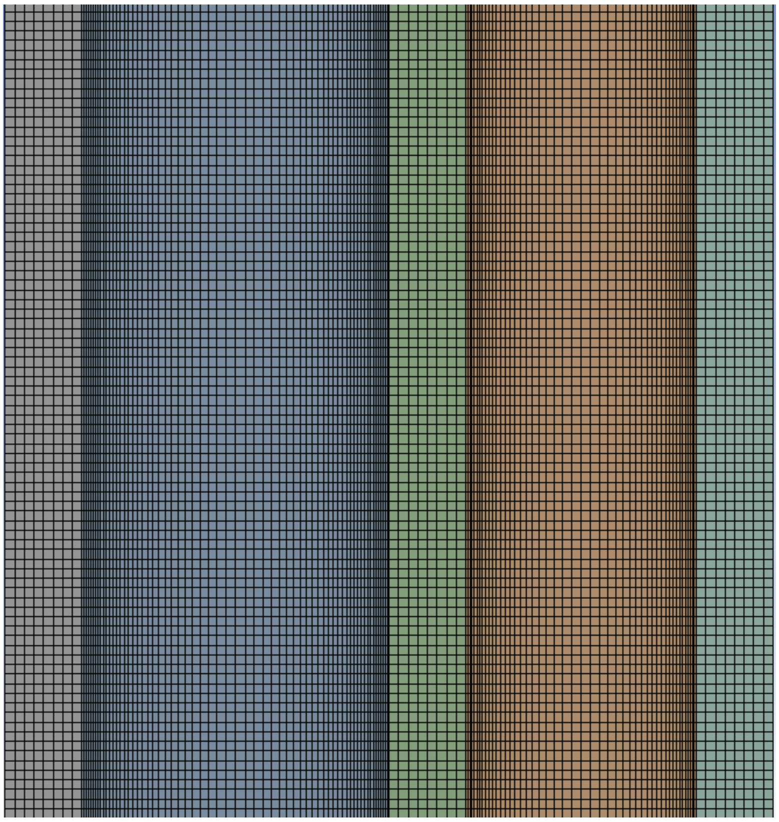


Figure 3.4. Mesh structure section for air filled cavity (L_1 = 16 mm, L_2 = 12 mm)

The flow behavior in the boundary layer region is very complex. Because in fluid dynamics, the no-slip condition for viscous fluid assumes have zero velocity near the solid boundary. The velocity changes are very large and non-linear in the wall normal direction and it is difficult to capture this gradient correctly. Therefore, it needs to be analyzed better for the accuracy of the analysis. It is important to use high quality meshing in the boundary layer and it is defined as inflation in ANSYS Fluent. Inflation also reduce the computational time.[50] In current study, for the solid surfaces, uniform grid is used. Non-uniform grid is used for the fluid surfaces. Bias defined for the left and right sides of the gas cavity region, so the smaller grid spacing is used near the walls through the wall normal direction defined as x direction in the study. And bias factor is defined 5. Thus, high quality meshing elements were used in the boundary layer region as shown in the Figure 3.4.

Skewness and orthogonal quality are the quality measures of the cell which have significant impact of the simulation accuracy. The skewness value shows how to close to ideal a face or cell is. It is defined as the difference between the ideal shape of the cell and the shape of a cell. For a triangular or tetrahedral mesh in the most flows, maximum value of the skewness is 0.95. If the maximum value pass over the 0.95, the convergence of the solution becomes difficult. A value of 0 indicates equilateral cell which is the best. In contrast the skewness value, the orthogonal quality of the cell is better when the minimum value is close to 1. And in this study, quadrilateral faces are used which is close to ideal. Thus, the value of skewness is close to 0 and the value of the orthogonal quality is close to 1 as shown in the Table 3.3.

Table 3.3. Mesh quality of 16 mm and 12 mm gap width

	Mesh Metric (L = 16 mm)		Mesh Metric (L = 12mm)	
	Skewness	Orthogonal Quality	Skewness	Orthogonal Quality
Min	0.13057	1	0.13057	1
Max	0.13948	1	0.13976	1
Average	0.13089	1	0.13152	1

3.3.3. Problem Description and Solution Method

In this study, flow and heat transfer in triple pane windows are investigated numerically. Calculations are solved using a CFD code, ANSYS FLUENT 19.1. Double precision fluent module is used. The pressure based solver is preferred. Because pressure based solver is designed for incompressible flows while density based solver is designed for high speed compressible flows. Thus, the computation cost will be reduced for this incompressible flow simulation. For solution methods, SIMPLE scheme is employed for pressure-velocity coupling. Second-order Upwind Scheme is used as a discretization scheme for momentum and energy equations. The default values of Fluent are used as under-relaxation factors shown in Table 3.4.

Table 3.4. Under-relaxation factors

Under-relaxation factor	value
Pressure	0.3
Density	1
Body forces	1
Momentum	0.7
Turbulence kinetic energy	0.8
Turbulence dissipations rate	0.8
Turbulent viscosity	1
Energy	1

Heat transfer by radiation has also considered in this study. Because more than half of the heat is transferred by radiation mechanisms especially for normal float glass windows. In recent studies, the importance of the radiation is emphasized with including and excluding radiative heat transfer in the calculations.[10] So the Surface-to-Surface (S2S) radiation model is selected in this study. The visual factors are taken as the average value of 1.0 due to the small size of the air gap between the panes. And this model calculates the view factor between all surfaces in the solution domain. If the energy equations in Fluent is on, Fluent computes conduction heat transfer in all fluid and solid zones.[45] So, the energy equation in Fluent is defined. Solar heat gain, energy loss by infiltration and heat loss through the window frame are not taken into account in the calculations.

The flow is accepted as turbulent natural convection for the air in the cavity. In natural convection studies, the Reynolds number no longer characterizes the flow. Rayleigh number (Ra) is used as a non-dimensional parameter for the natural convection heat transfer driven by the buoyance forces against viscous forces. When Ra>1708, the buoyant force arouses the fluid and starts natural convection currents in the cavity. The flow regimes from laminar to turbulent determined according to the critical value of Rayleigh number which is 3 x 10^5. For upper number of Rayleigh means that the fluid becomes turbulent.[38] Rayleigh number is calculated as:

$$Ra_L = \frac{g\beta(T_1 - T_2){L_c}^3}{v^2} Pr \tag{3.4}$$

where the thermophysical properties of the fluid are determined according to the average temperature of the fluid which is T_{avg}.

While convergence criteria are decreasing, the iterations increasing for obtaining precise results. The minimum recommended value of convergence criteria is 1E-04 for accuracy of the simulation. In the present study, convergence criteria are assumed to be 1E-06 for continuity, velocity, turbulence and energy equations. The convergence of the equations takes place after approximately 2000 iterations with the mesh structure determined in the simulations. When the convergence is achieved, the results are getting stable. A representative case of residual history is shown in Figure 3.5.

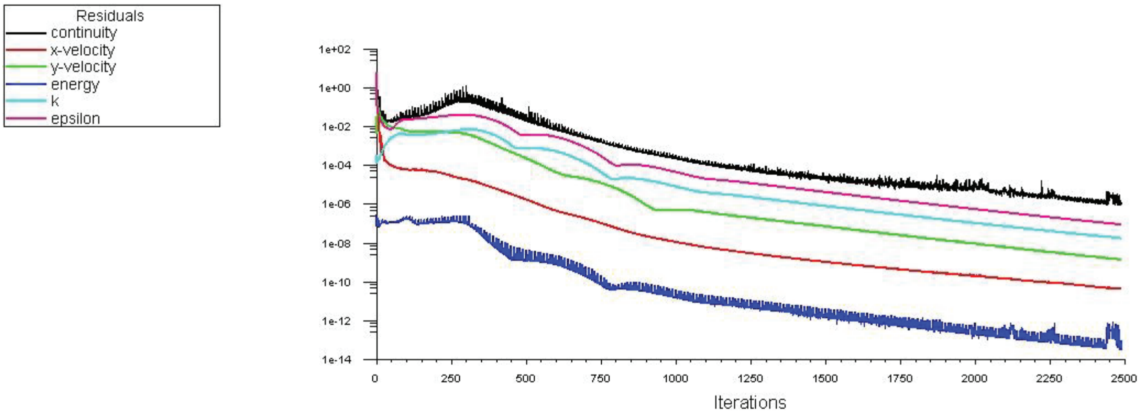


Figure 3.5. Convergence history of residuals

In low temperature differences in the gas layer, the occurrence of multicellular flow is less observed. Because, when the temperature difference increases, the buoyancy force and turbulence also increase and multicellular pattern takes place in the flow.[14] Therefore, the iterations and time of the convergence are prolonged with k-epsilon model in low temperature differences. Although it is able to simulate with laminar model with less time, turbulence in the flow is difficult to capture with steady state laminar model. For such an analysis, the k-epsilon model is still recommended as it includes the transitional regime.

In the light of this information mentioned in this chapter, the following assumptions were considered in the present study:

- The fluid is Newtonian and incompressible.
- The flow is assumed to be two-dimensional, steady and turbulent.
- RNG k-epsilon model is selected for the turbulence model which is analyzed in the studies as referenced.[23,51] The study indicated that the RNG k-epsilon is more realistic model comparing other turbulence models for this type of studies.[23,51]
- The “Enhanced wall function” is specified in the turbulence model.[23]
- Incompressible ideal gas approximation is defined for calculating density of air by the equation of state.[8]
- The other thermophysical properties of gases are assumed to be constant at average temperature.

Similar studies conducted and published in recent years are in line with the approaches determined in this study as shown in Table 3.5.

Table 3.5. Details of approximations, assumptions, geometries and solution schemes used by earlier researchers in recent years

	1	**2**	**3**	**4**	**5**	**6**	**7**
CFD Study	**[39]**	**[40]**	**[23]**	**[14]**	**[9]**	**[8]**	**[10]**
Published year	2000	2006	2007	2009	2011	2015	2015
Boussinesq approximation	+	+	+	+	-	-	-
Ideal Gas approximation	-	-	+	-	+	+	+
Radiation Heat Transfer	-	-	-	-	+	+	+
Transient	-	-	-	+	-	+	+
Steady	+	+	+	-	+	-	-
Double Pane Window	+	+	+	+	+	+	+
Triple Pane Window	-	-	-	-	+	+	+
Quadruple Pane Window	-	-	-	-	-	+	+
Grid Number	3751 (a gap)	3751 (a gap)	1 mm grid size	1000 (a gap)	31000 - 84000 (total)	32000 (a gap)	10000 – 50000 (total)
Boundary Conditions	Constant temperature	Both	Convection	Constant temperature	Constant temperature	Convection	Constant temperature
Flow	Laminar	Laminar	Turbulent	Laminar	Laminar	Laminar	Laminar
Pressure& Velocity	-	-	SIMPLE Algorithm	SIMPLE Algorithm	SIMPLE Algorithm	SIMPLE Algorithm	SIMPLE Algorithm
Radiation Model	-	-	Surface to Surface	-	Surface to Surface	Surface to Surface	Surface to Surface
Turbulence Model	-	-	RNG k-E	-	-	-	-

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the U-values of the different glazing systems obtained from the CFD simulations results are compared. The purpose of the CFD simulations is to investigate fluid flow and heat transfer characteristics of the triple pane windows with a parametric study. The results obtained in the calculations are interpreted with graphics. Calculations are made for triple pane windows considering various cavity widths with different emissivity coatings and different temperature ranges. In addition the effect of radiation heat transfer on the total heat transfer is also emphasized with this study. Simulation results display also temperature distributions and velocity fields for different scenarios of the glazing systems.

4.1. Validation of the Simulation Results

The numerical method of the study is validated according to results of experimental data of ElSherbiny et al.[42] and numerical data of the referenced researches which is studied from Gustavsen and Thue[44] and studied from Arıcı et al.[8] For comparison with these studies, similar geometries are identified that have similar Rayleigh numbers (Ra_L) and aspect ratios (H/L). For these validation studies, computations are performed for double pane windows with air filled cavity. The width (L) of the window cavity is considered according to Ra_L and the height (H) of the cavity is determined considering the aspect ratios. Radiation heat transfer is not included in the calculations. As seen in the Table 4.1. the computed results of the study have good agreement with the data of experimental[42] and numerical studies.[8,44] The maximum deviation is about 6%. The Nusselt numbers are obtained from with the equation:

$$Nu = \frac{qL}{(T_1 - T_2)k} \tag{4.1}$$

where T_1 and T_2 are the temperatures of the surface of the glass panes.

Table 4.1. Comparison of average Nusselt numbers

H/L	***Ra$_L$***	**Present Study**	**Numerical Study**	**Numerical Study**	**Experimental Study**
			[8]	[44]	[42]
40	1000	1.007	1.012	1.011	1.000
	5000	1.093	1.092	1.093	1.030
	10000	1.265	1.298	1.256	1.294
	15000	1.399	1.424	-	1.492
80	1000	1.004	1.005	1.006	1.000
	5000	1.047	1.042	1.047	1.023
	10000	1.196	1.180	-	1.260
110	1000	1.004	1.004	-	1.000
	3500	1.020	1.023	-	1.012
	5000	1.034	1.033	-	1.060

Table 4.1 shows increasing the number of Rayleigh (Ra_L) increases the number of Nusselt when the aspect ratio is constant.

The U-values computed by the correlation (Equation 3.3) with the simulation data have good agreement while comparing literature data of results.[15],[8] as shown in Table 4.2. Thus, the proposed model also validated with the data of ASHRAE standards of centre of glass U-value. According to ASHRAE, all heat transfer coefficients are based on winter conditions -18°C outdoor air temperature. Indoor air temperature is 21°C. Solar flux accepted zero. So, the computations perform according to these conditions. Table 4.2 shows the comparison of air filled double glazing units and air filled triple glazing units with different gap widths under specified conditions. The maximum deviation is again 6%.

Table 4.2. Comparison of the U-values computed by the correlation (Equation 3.3) and data of ASHRAE[15] and referenced study. [8]

			Centre of glass U-value (W/m^{2}K)		
Glazing type	**Gas filling**	**Gap width (mm)**	**[15]**	**[8]**	**Present study**
Double glazing	Air	6.4	3.12	3.33	3.30
		12.7	2.73	2.95	2.88
Triple glazing	Air	6.4	2.16	2.24	2.22
		12.7	1.76	1.89	1.84

4.2. The Effect of Cavity Width on Heat Transfer

For the triple pane windows, it has been determined that increasing the cavity dimension from 12 mm to 16 mm reduces the amount of heat transfer for all temperature differences calculated by the inside and outside temperature values which are defined four different climatic condition in Turkey. So, the heat flux is inversely proportional to the cavity width as can be seen in the Figure 4.1 which is obtained from the calculations. This correlation was previously explained in Equation physically.

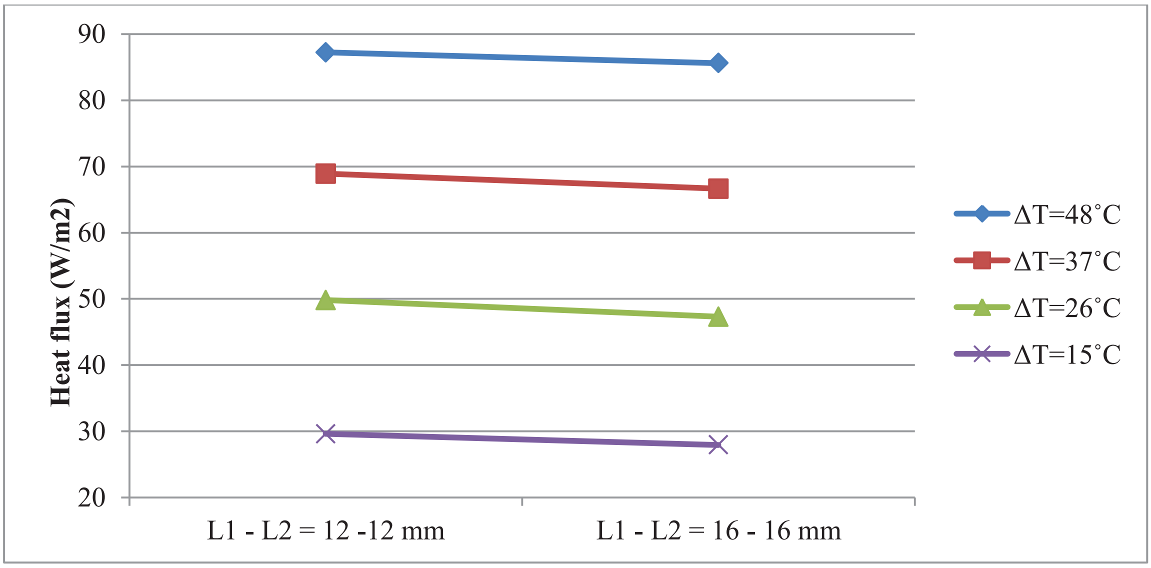


Figure 4.1. Comparison of the heat flux considering the gap width and temperature differences through triple pane windows with standard glass (Ɛ = 0.84)

As the air layer thickness between the glass panes is smaller, conduction is the main mechanism of the heat transfer. So, the heat transfer rate decreases very rapidly with the increasing of air layer thickness in smaller cavity width. Since the air is a material with low conductivity, it acts as an insulating material. However, for larger thickness, convection heat transfer effect of the total heat transfer rate is more observable. It can be seen in the Figure 4.2 below, the decrease in the U-value continues with a lower slope in the widths after 12 mm where the ΔT=26°C. It shows that the conduction and convection heat transfer rate are comparable in the range of 12 mm to 16 mm. Because increasing gap width increase the convection heat transfer while decreasing the conduction heat transfer. Therefore, there is no significant decrease in the heat loss with further increase in the gap width.

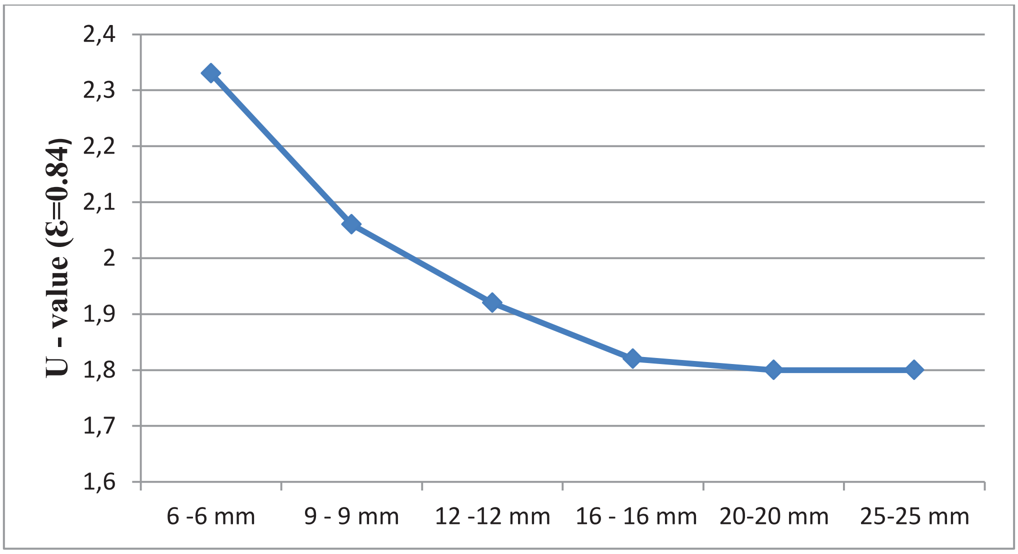


Figure 4.2. Variation of U-value of the triple pane windows according to cavity width at 26°C temperature difference with standard glass (Ɛ = 0.84)

If the Nusselt number equals to 1, it is indicated as the conduction is the only mechanism of the heat transfer. For the larger thickness, Nu increases with the gap width increases. It means natural convection heat transfer dominates the conduction heat transfer. The Figure 4.3 shows the change in the Nusselt numbers for four scenarios which as 12-12, 16-16, 12-16 and 16-12 mm gap widths glazing systems' cavity at the cold side at different temperature differences.

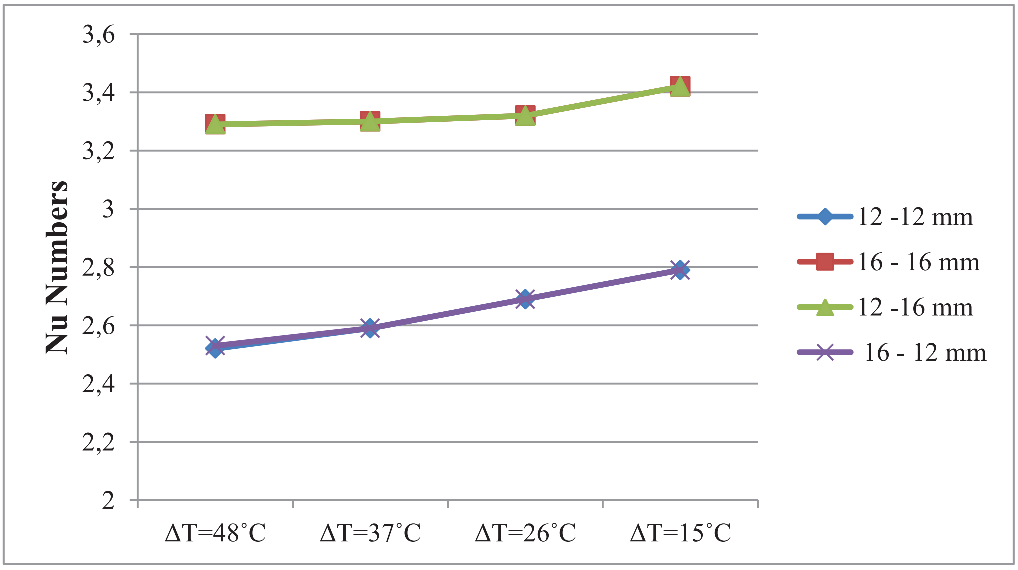


Figure 4.3. Variation of the average Nusselt number considering air layer thickness in the cavity at the cold side (Ɛ = 0.84)

4.3. The Effect of Flow Patterns on Heat Transfer

It is known that while the width of the air layer is small, the heat transfer mechanism is only conduction and the fluid has unicellular flow pattern. In this case, the increase of the air layer thickness to a certain gap width reduces heat losses. Since the heat transfer takes place also with convection after this width, the fluid movement starts due to increasing buoyancy force. Thus, the transition of unicellular to multicellular pattern occurs. And the heat transfer coefficient is increased. That is, as shown in the Figure 4.2, after the gap width of approximately 12 mm, the formation of multicellular pattern in the fluid reduces the decrease in heat transfer rate.

Not only the gap width but also the temperature gradient is an important parameter affecting the movement of the fluid inside the cavity. As a result of the calculations with a constant indoor temperature (20°C) and different outdoor temperatures, it is seen that when the temperature difference is low, the formation of the multicellular pattern starts at a higher range gap width.

4.4. The Effect of Temperature Difference on Heat Transfer

As mentioned in the previous section, in cases where the temperature difference is low, the formation of multiple cells in the fluid begins in larger gap widths. Because when the temperature difference increases the convection heat transfer increases. So, the fluid flow velocity increases also. And it is seen the unsteady flow behavior due to moving and reforming of cells in the cavity.

When the temperature difference is 15°C and the emissivity of the glass is 0.1 U-value can be reduced to 0.92 W/m^{2}K with using the glazing scenario which is 16-16 mm gap width. The other scenarios that the cavity width of 12-16 mm, 16-12 mm and 12-12 mm have the U-value of 0.99, 0.99 and 1.07 W/m^{2}K respectively. Then, the heat flux can be reduced by 15% using a 16-16 mm wide cavity instead of the 12-12 mm wide cavity in this temperature difference. The following graphic shows the heat flux of these scenarios due to gap width and the temperature differences. It is shown as from the Figure 4.4 the large cavity width is more effective in warm climates. Besides, in the cold climates the effect of the wide range cavity width is not as noticeable as the warm climates. Even as it is seen from the chart, it is possible to capture the same heat fluxes with the glazing having cavity width of 16-16 mm and 12-16 mm in the 48˚C temperature difference. Even under these conditions, it is possible to reduce the heat transfer about 2% by using 16-12 mm spaced glazing instead of 12-12 mm spaced glazing.

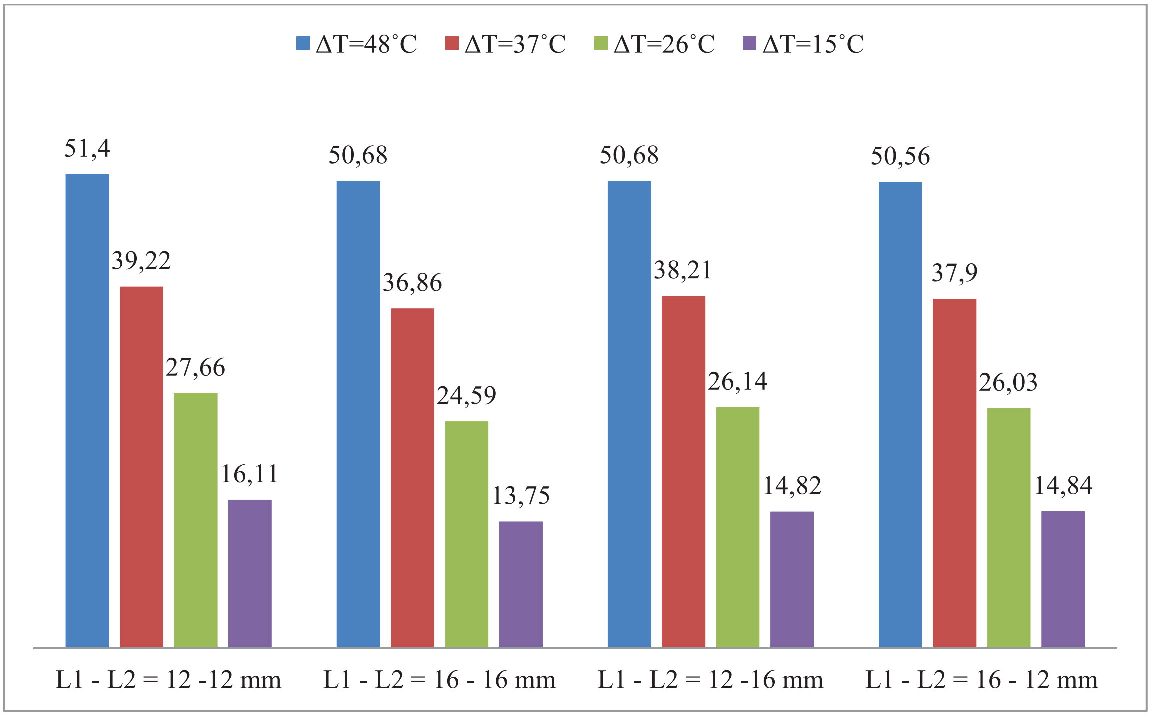
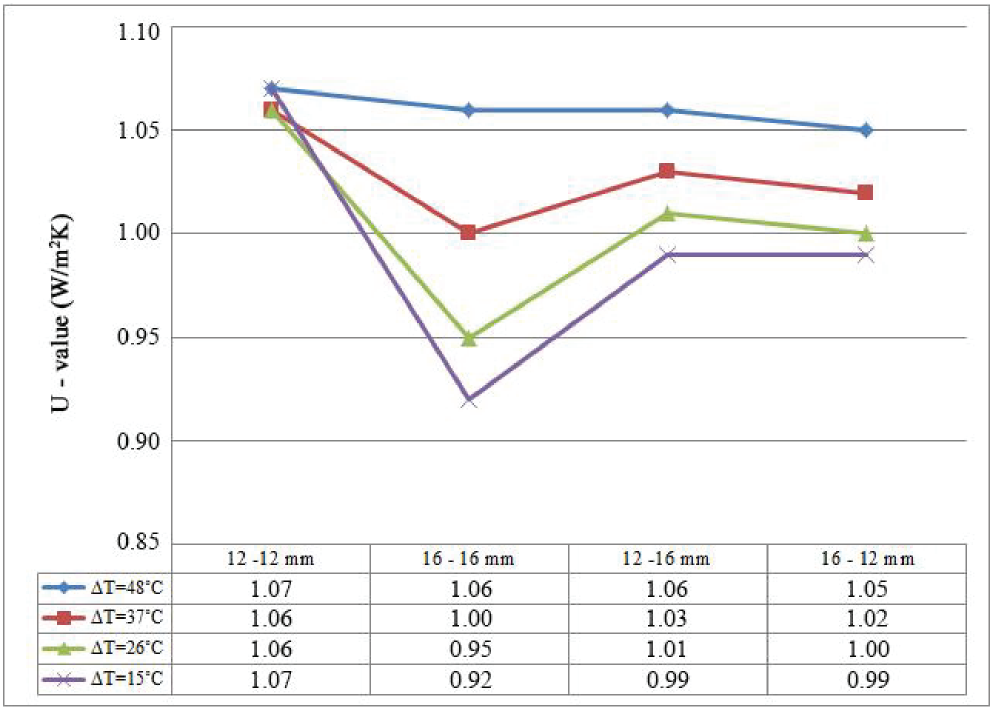


Figure 4.4. Variation of heat flux due to cavity widths and temperature differences in the triple glazing having low-e coating material on surface of #2 and # 5 (Ɛ=0.1)

It can be seen from the U-values graphic obtained from calculation results below. The Figure 4.5 also shows the numerical results of the computations according to cavity widths and different outdoor temperatures of the determined cities. When the temperature difference is 48℃, using with low-e coating material (Ɛ=0.1) on the glass surface of #2 and #5 on the glazing of 16-12 mm gap width gives the best result. So, the scenario of 16-12 mm gap widths is suitable for the cold climates. When the temperature difference is 15℃, the 16-16 mm of gap widths scenarios gives the best result and it is suitable for the warm climates. And the window having 12-12 mm gap width provides worse insulation while comparing other alternatives at all temperature differences between inside and outside of the window panes. These are shown in the Figure 4.5.



	12 -12 mm	16 - 16 mm	12 -16 mm	16 - 12 mm
◆ ΔT=48°C	1.07	1.06	1.06	1.05
■ ΔT=37°C	1.06	1.00	1.03	1.02
▲ ΔT=26°C	1.06	0.95	1.01	1.00
× ΔT=15°C	1.07	0.92	0.99	0.99

Figure 4.5. Effect of the cavity width and the temperature difference on the U-value in the triple glazing having low-e coating material on the surfaces of #2 and #5 (Ɛ=0.1)

In the triple pane windows, the temperature difference is higher in the cavity at the cold side. Since the radiation heat transfer is proportional to the 4th power of the temperature, to compensate the heat transfer in each cavity a greater temperature difference occurs on the cold side cavity.[10] This causes larger air velocities on the cold side. And with the effect of the buoyancy forces, natural convection also increases. Therefore, reducing the gap width on the cold side reduces the fluid flow velocity and the heat transfer. Thus, the total heat transfer coefficient, U-value, decreases especially in the cold climates. The scenario of 16-12 mm gap width glazing system better results in the high temperature difference can be explained in this way.

Due to the results of the scenario of 16-12 mm gap width, the simulations are made with changing the surface emissivity values at high temperature differences. Thus, the 16-16 mm and 16-12 mm gap widths are compared for the cold climates. In the next section 4.6, these results were examined with the effect of low-e coating.

Another important aspect to be noted here is that there is no significant change in the scenarios of 12-12 mm gap width due to temperature differences with low-e coating material. It is because the main mechanism of heat transfer is the conduction in these cavity widths.

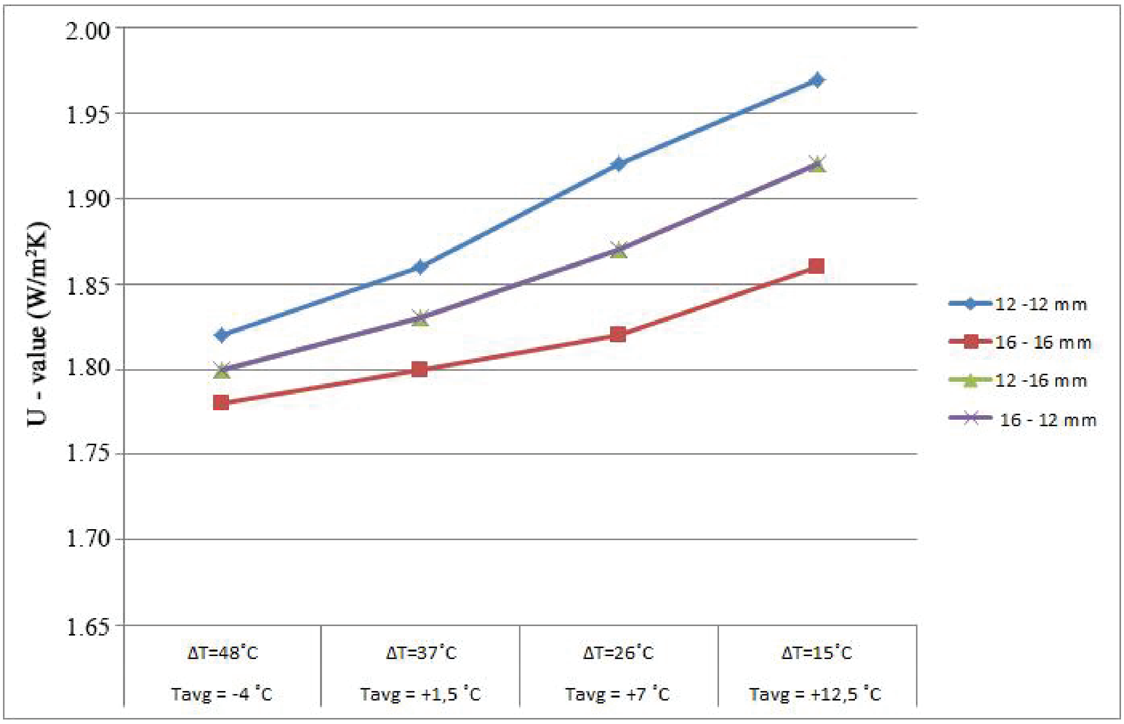


Figure 4.6. Variation of U-value due to temperature differences and gap widths in the triple pane windows with standard glass (Ɛ=0.84)

According to the simulation results, the U-value increases when the temperature differences, between inside and outside window panes, decreases in glazing systems having the same gap width. The expectation results of the analysis of glazing system having standard glass (Ɛ=0.84), while temperature difference decreasing, the U-value also decrease. However, the indoor temperature of this analysis is assumed to be constant so the low temperature difference means that the higher average temperature for this study. Thus, although decreasing the temperature difference the U-value increase because of the increasing average temperature. It causes also increasing the conductivity of the gas in the cavity. In addition, since the radiation heat transfer is proportional to the 4th power of the temperature, the radiation heat transfer rate is increased in the high temperatures. This is the most important reason for increasing *h* and U-values. Because as seen in the Figure 4.7 below, on the contrary of standard glass, decreasing temperature difference in the low-e coating glass decrease the U-value and *h*. It means that effect of the radiation heat transfer on the total heat transfer is reduced.

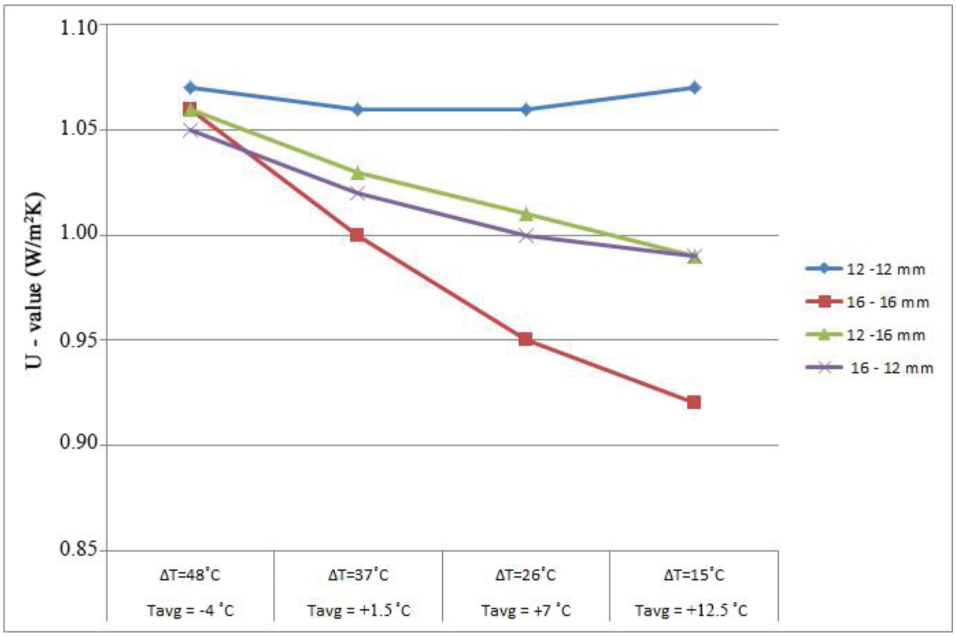


Figure 4.7. Variation of U-value due to temperature differences and gap widths in the triple glazing having low-e coating material on the surfaces of #2 and # 5 (ε=0.1)

The effect of mean temperature, temperature difference and the emissivity values of the glass surface on *h*, as shown in the Table 4.3 in the referenced data, confirms the results also.[38]

Table 4.3. The heat transfer coefficient h_s for the air space trapped between the two vertical parallel glass layers for 13mm air spaces
(Source: [38], modified from Building Materials and Structures, Report 151, U.S. Dept. of Commerce)

Air space thickness = 13 mm					
T_{avg} (˚C)	ΔT (˚C)	h_s, W/m^2 °C			
		$\varepsilon_{effective}$			
		0.72	0.4	0.2	0.1
0	5	5.3	3.8	2.9	2.4
0	15	5.3	3.8	2.9	2.4
0	30	5.5	4.0	3.1	2.6
10	5	5.7	4.1	3.0	2.5
10	15	5.7	4.1	3.1	2.5
10	30	6.0	4.3	3.3	2.7
30	5	5.7	4.6	3.4	2.7
30	15	5.7	4.7	3.4	2.8
30	30	6.0	4.9	3.6	3.0

4.5. Temperature Distribution and Velocity Profile

The temperature distributions for four different scenarios of triple glazed units at the 48°C temperature difference namely a, b, c and d in the Figure 4.8. The emissivity of the glass is 0.84 as a standard glass. And the gap widths are different.

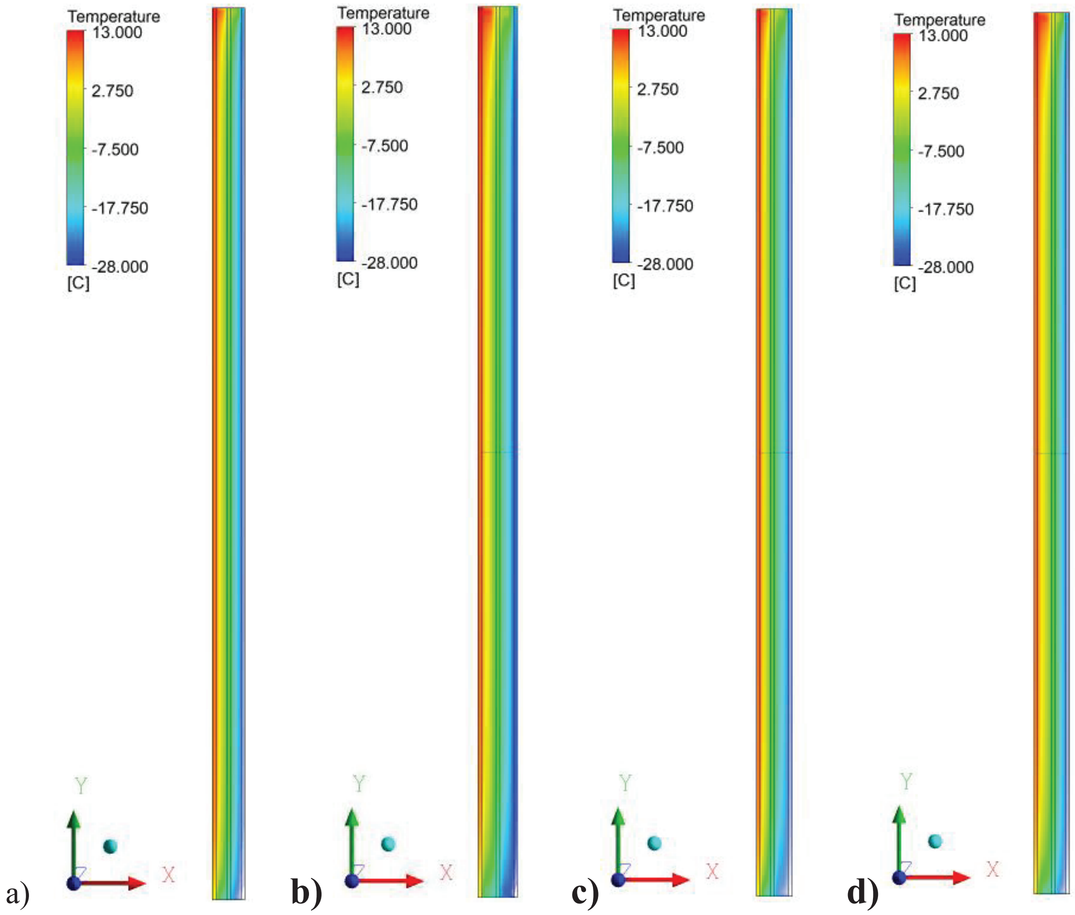


Figure 4.8. Temperature distribution of triple pane windows ($\varepsilon=0.84$) due to gap widths at $\Delta T=48$°C for scenarios a, b, c, and d. (a) L1 – L2 = 12-12 mm (b) L1 – L2 = 16-16 mm (c) L1 – L2 = 12-16 mm (d) L1 – L2 = 16-12 mm

The temperature distributions of the glazing units differ from the gap widths as shown in the Figure 4.8. The maximum and minimum temperature values in the air filled cavity are different in all scenarios. However higher temperature values are seen in the upper regions of the cavities than in the lower regions similarly. Increased temperature along the y-axis as a result of the rise of warm air reaches to the highest value when close to the upper limit of the cavity and then shows a sudden decline. As can be seen from both temperature distributions figures and temperature profile graphics given below, the temperature difference in the cavity at cold side is more than the other due to radiation. The figures, namely as a, b, c and d, show the effect of the gap width on the temperature profile.

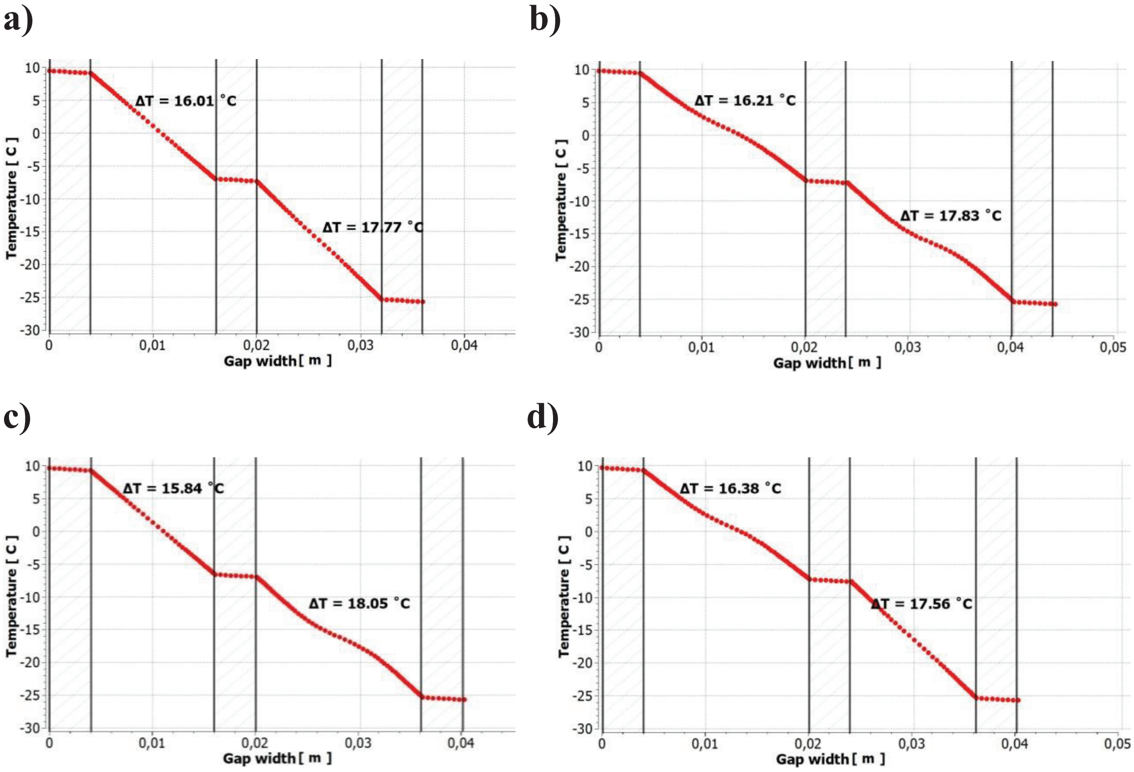


Figure 4.9. Temperature profiles of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=48°C for scenarios a, b, c, and d. (at y/H=0.5) (gap width 0 m is inside surface) (a) L_1–L_2 = 12-12 mm (b) L_1–L_2 = 16-16 mm (c) L_1–L_2 = 12-16 mm (d) L_1–L_2 = 16-12 mm

As seen in the Figure 4.9 increasing the width of the cavity distorts the linear temperature variation. This is due to the increase of convection heat transfer. Although small gap width as 12 mm, linearity is slightly distorted because of the high temperature difference especially in the cold side cavity.

This high temperature difference causes also relatively high air velocities in the cavities of cold side. The high air velocity seen in the cavity on the cold side is not only due to the high temperature difference in this gap. It is about also the density of the fluid. In the literature, the studies that the radiation was not included and the calculations with boussinesq approach were examined. And it was shown that the velocity profiles in the two cavities were the same and physically meaningless.[10] Therefore, calculations in this study are made by using ideal gas approach and including radiation heat transfer. As seen in the Figure 4.10, the fluid velocity on the cold side cavity is higher except the scenarios of d ($L_1 - L_2$ = 16 – 12 mm) as mentioned before. Reducing the gap width on the cold side cavity decrease the velocity and the heat transfer rate.

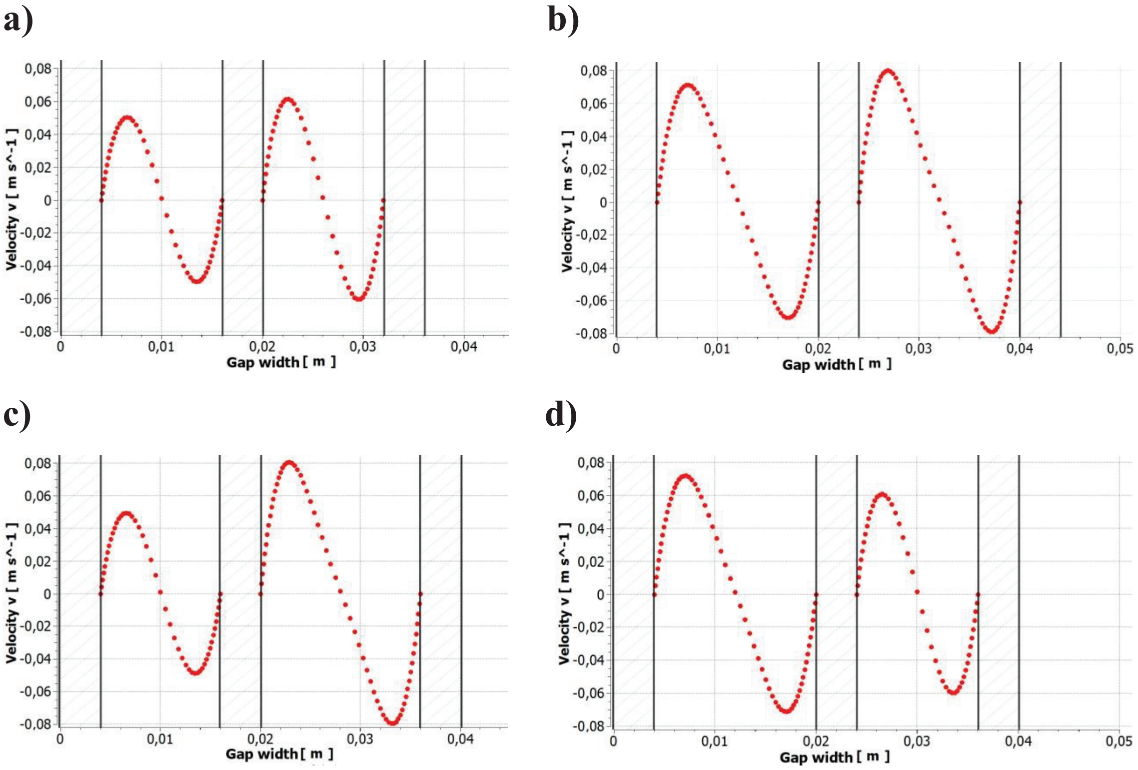


Figure 4.10. Velocity profiles of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=48°C for scenarios a, b, c, and d. (at y/H=0.5) (gap width 0 m is inside surface) (a) L_1–L_2 = 12-12 mm (b) L_1–L_2 = 16-16 mm (c) L_1–L_2 = 12-16 mm (d) L_1–L_2 = 16-12 mm

Maximum velocity occurs in the cold side cavity of the glazing having 16-16 mm and 12-16 mm gap width is about 8 cm/s and minimum velocity occurs in the 12-12 mm gap width is about 4 cm/s.

The temperature distributions of the triple glazed units at the 37°C temperature difference according to four different gap width scenarios namely a, b, c and d are shown in the Figure 4.11. The emissivity of the glass is 0.84 as a standard and the gap width 0 m is inside surface.

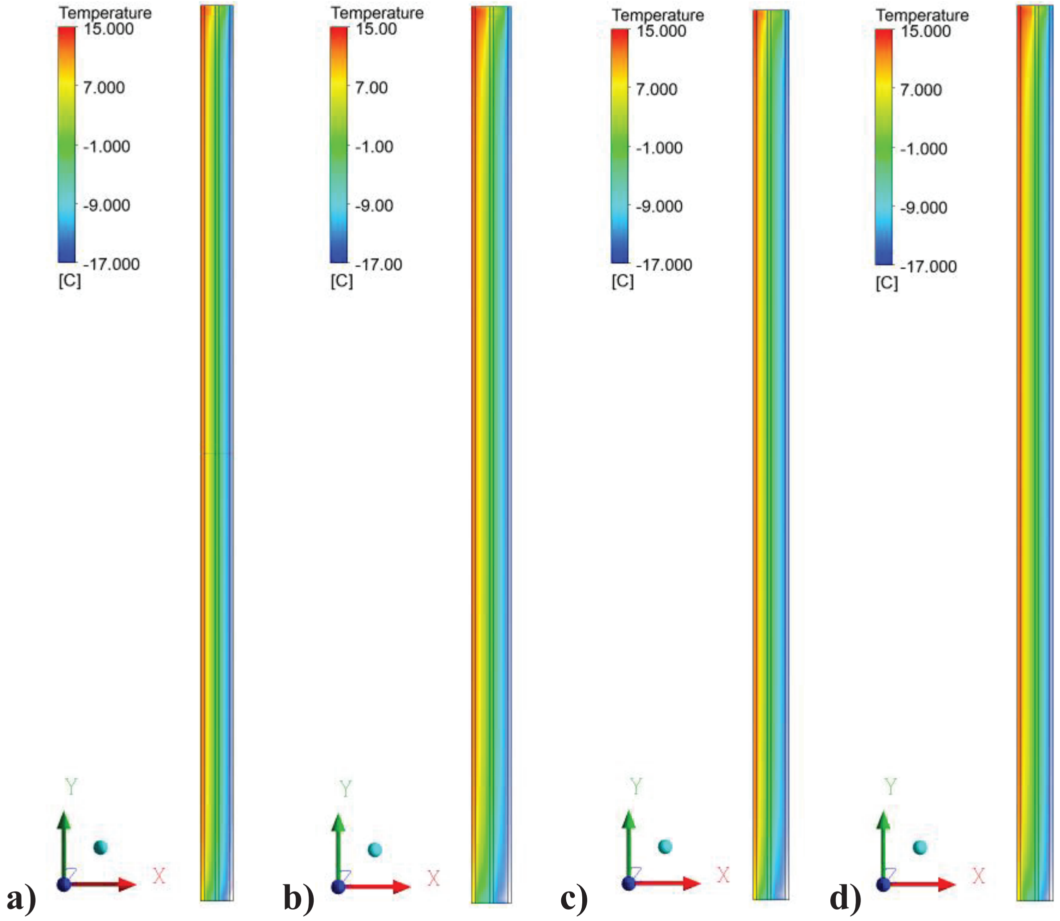
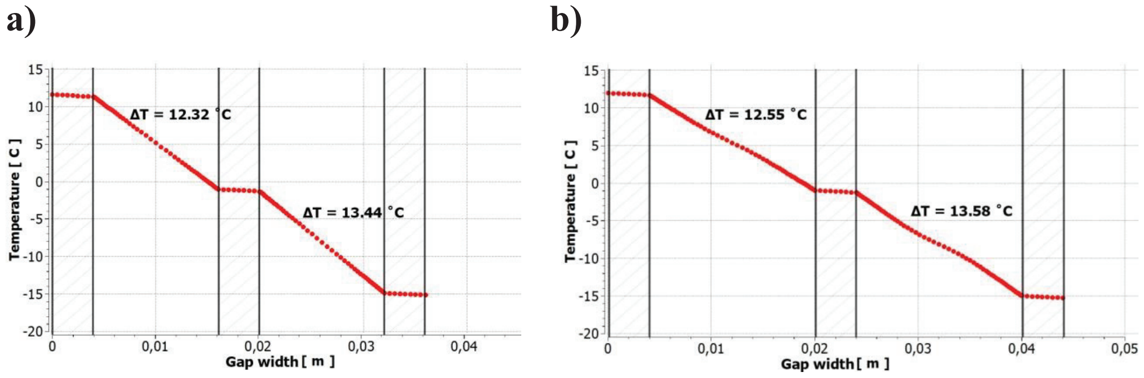


Figure 4.11. Temperature distribution of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=37°C for scenarios a, b, c, and d. (a) L1 – L2 = 12-12 mm (b) $L_1 - L_2 =$ 16-16 mm (c) $L_1 - L_2 =$ 12-16 mm (d) $L_1 - L_2 =$ 16-12 mm

The temperature distributions differ from the gap widths as seen in the Figure 4.11. The maximum and minimum temperature values in the air filled cavity are different in all scenarios. The Figure 4.12 below shows the temperature profiles of these scenarios according to cavity dimensions at temperature difference of 37°C.



c) d)

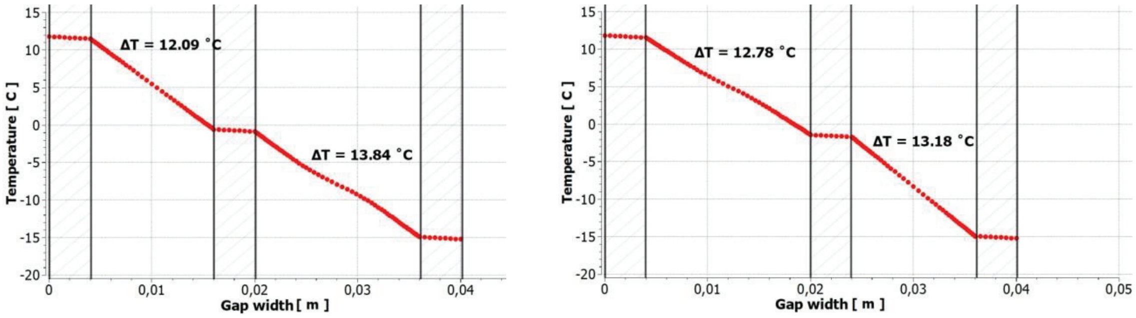


Figure 4.12. Temperature profiles of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=37°C for scenarios a, b, c, and d. (at y/H=0.5) (gap width 0 m is inside surface) (a) L_1–L_2 = 12-12 mm (b) L_1–L_2 = 16-16 mm (c) L_1–L_2 = 12-16 mm (d) L_1–L_2 = 16-12 mm

The linear temperature variation seen in the 12mm wide cavity, is not seen in the cavity of 16mm wide. Because at the larger gap widths temperature profiles become nonlinear. In the temperature difference of 48°C the linearity is distorted even in 12 mm wide gap. But it is not seen in this temperature range (ΔT=37°C).

a) b)

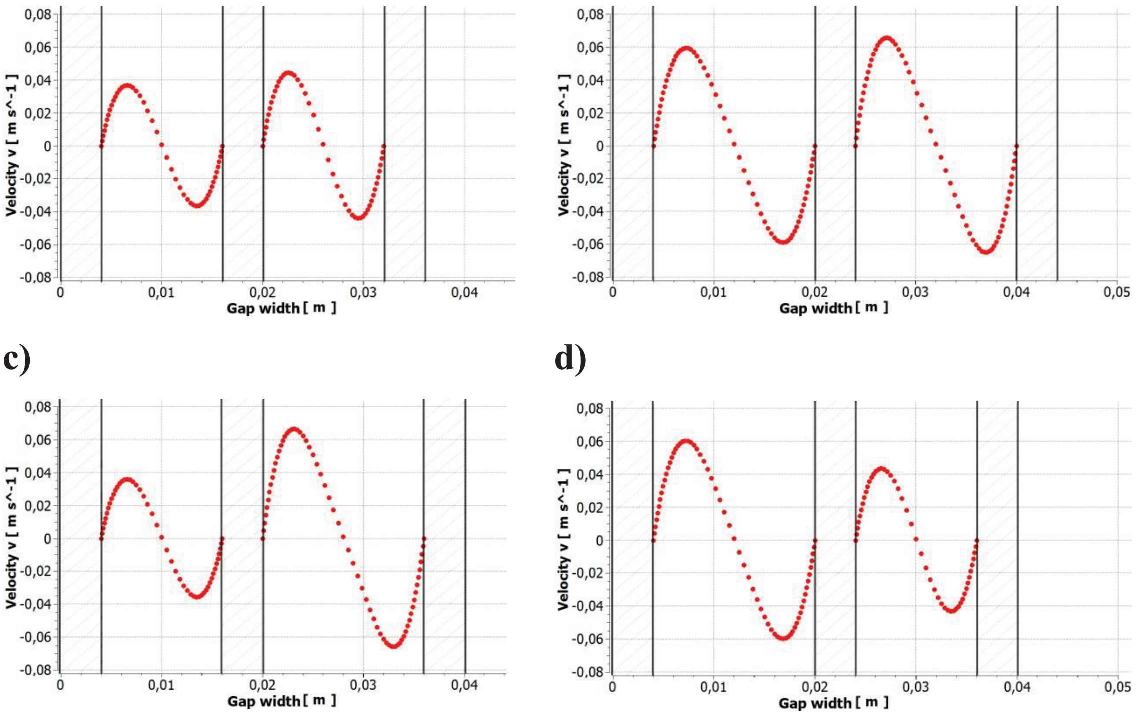


Figure 4.13. Velocity profiles of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=37˚C for scenarios a, b, c, and d. (at y/H=0.5) (a) L_1–L_2 = 12-12 mm (b) L_1–L_2 = 16-16 mm (c) L_1–L_2 = 12-16 mm (d) L_1–L_2 = 16-12 mm

Maximum velocity occurs in the cold side cavity of the glazing having 16-16 mm and 12-16 mm gap width is about 6 cm/s and minimum velocity occurs in the 12-12 mm gap width is about 4 cm/s at the 37°C temperature difference.

And the temperature distributions where temperature difference is 26°C according to four different gap width scenarios in same conditions as represent:

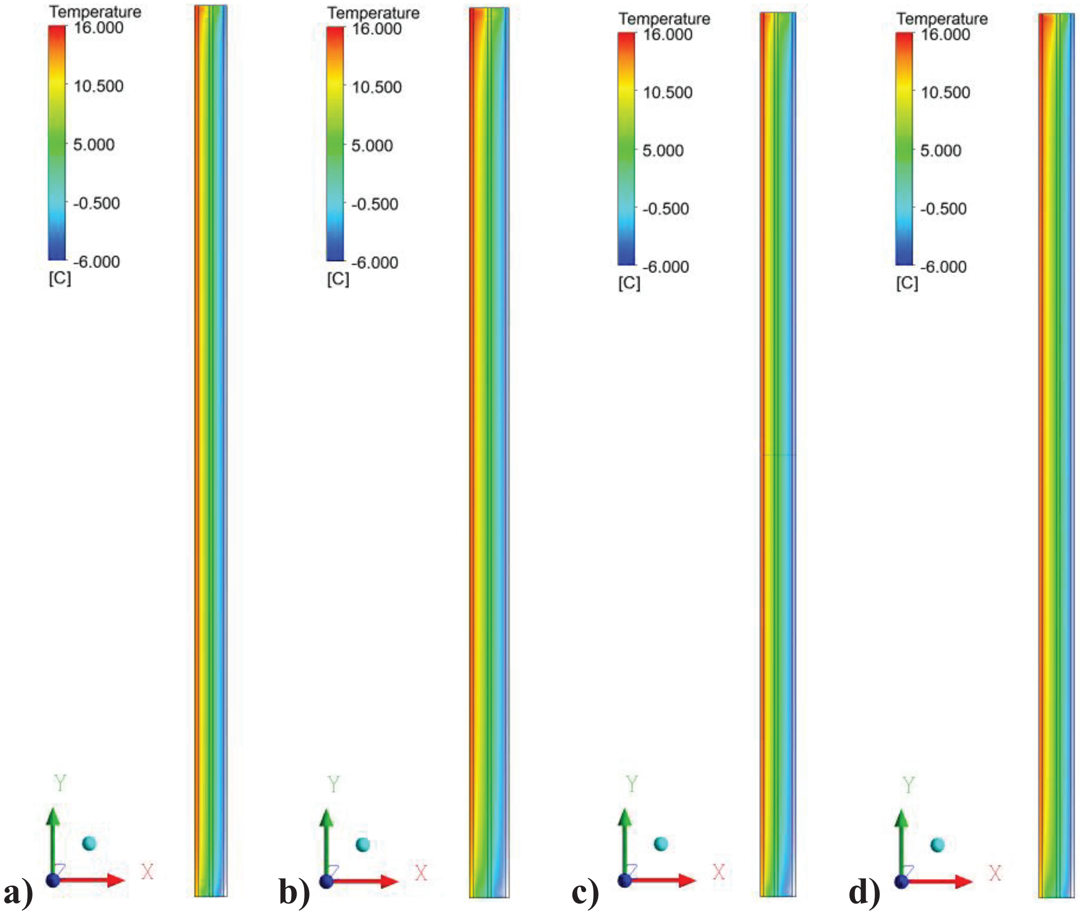
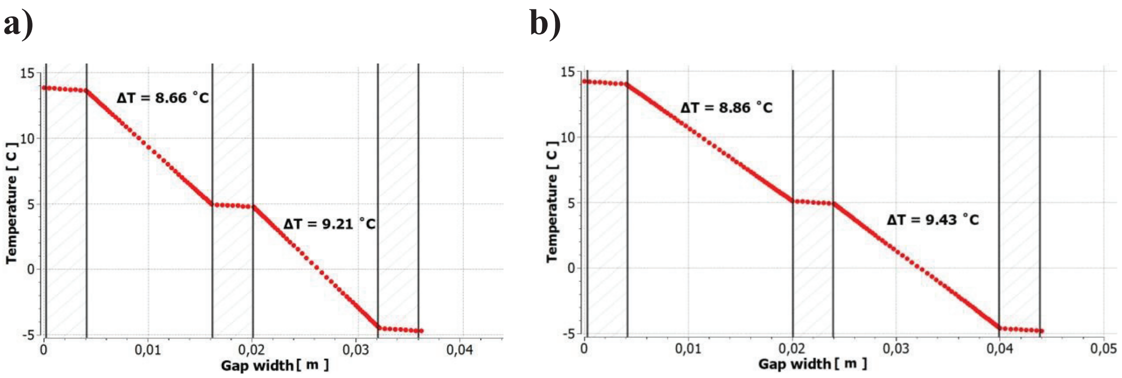


Figure 4.14. Temperature distribution of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=26°C for scenarios a, b, c, and d. (a) L1 – L2 = 12-12 mm (b) $L_1 - L_2 =$ 16-16 mm (c) $L_1 - L_2 =$ 12-16 mm (d) $L_1 - L_2 =$ 16-12 mm



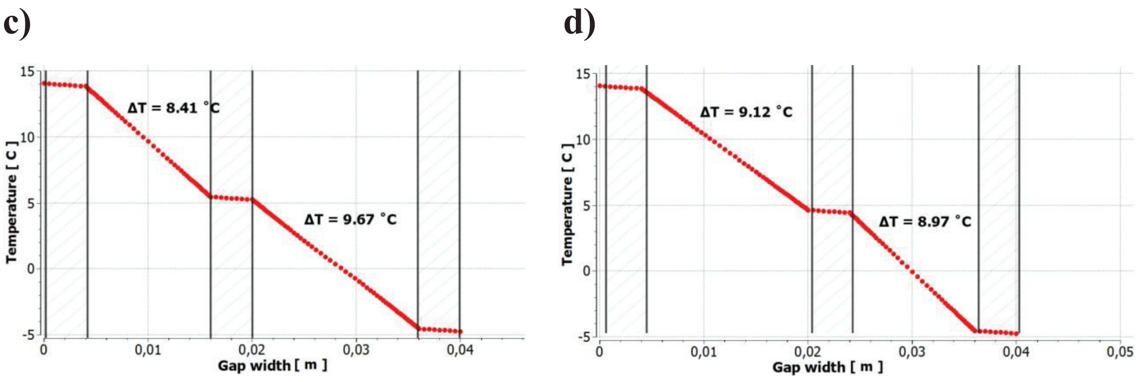


Figure 4.15. Temperature profiles of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=26°C for scenarios a, b, c, and d. (at y/H=0.5) (gap width 0 m is inside surface) (a) L_1–L_2 = 12-12 mm (b) L_1–L_2 = 16-16 mm (c) L_1–L_2 = 12-16 mm (d) L_1–L_2 = 16-12 mm

As expected result the temperature difference in the cavity at the cold side is higher except the scenario of d. With reducing the gap width at the cold side reduced the temperature difference also. All temperature profiles approached the linear profile and maximum and minimum velocity is decreased in this temperature range (ΔT=26°C).

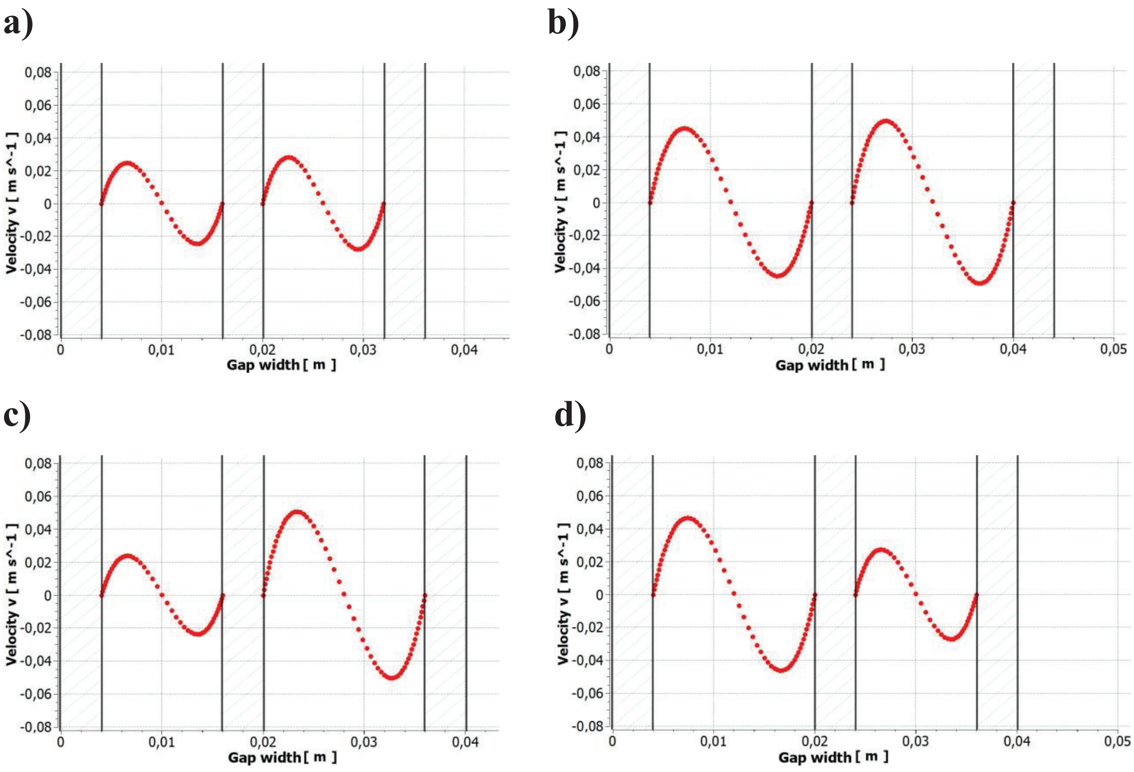


Figure 4.16. Velocity profiles of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=26°C for scenarios a, b, c, and d. (at y/H=0.5) (a) L_1–L_2 = 12-12 mm (b) L_1–L_2 = 16-16 mm (c) L_1–L_2 = 12-16 mm (d) L_1–L_2 = 16-12 mm

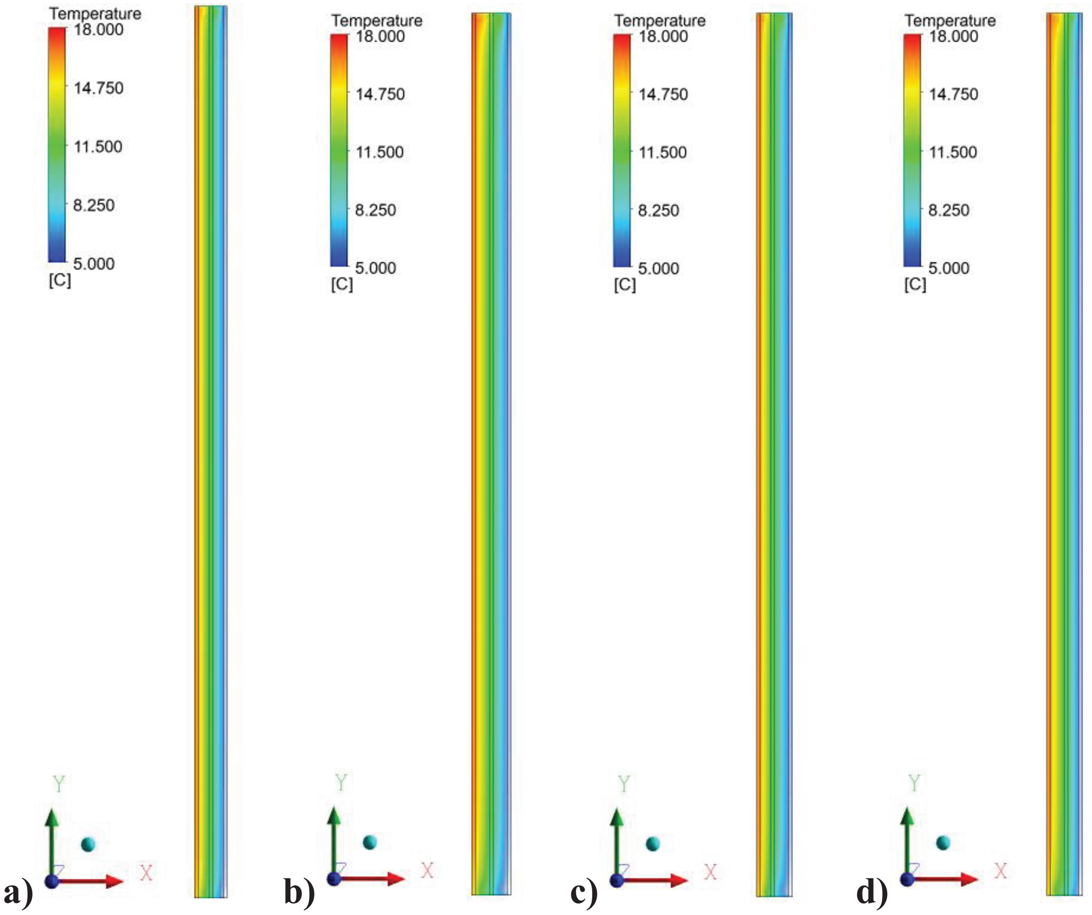
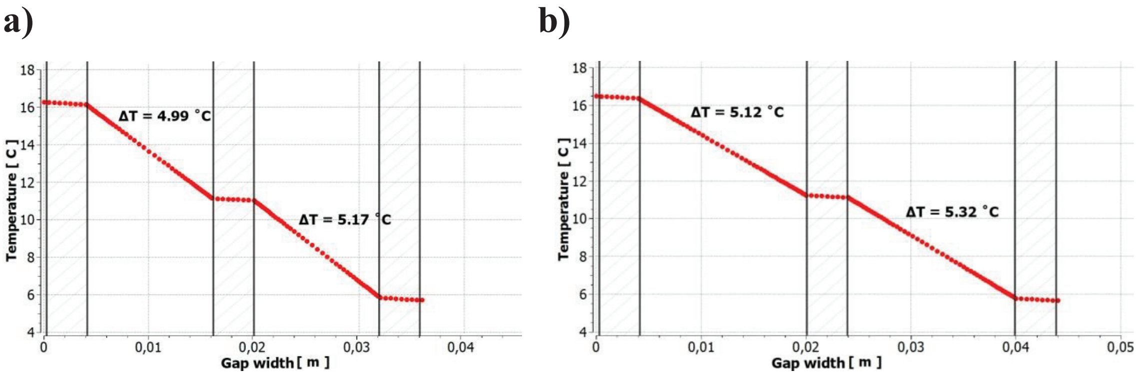


Figure 4.17. Temperature distribution of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=15°C for scenarios a, b, c, and d. (a) L1 – L2 = 12-12 mm (b) $L_1 - L_2$ = 16-16 mm (c) $L_1 - L_2$ = 12-16 mm (d) $L_1 - L_2$ = 16-12 mm

When the temperature difference is 15°C, the temperature profiles become linear for all gap widths. The linearity of the temperature profile means that the major heat transfer mechanism is the conduction. Therefore, the use of glass with a width of 16-16 mm is more efficient in this temperature range (ΔT=15°C) as mentioned before.



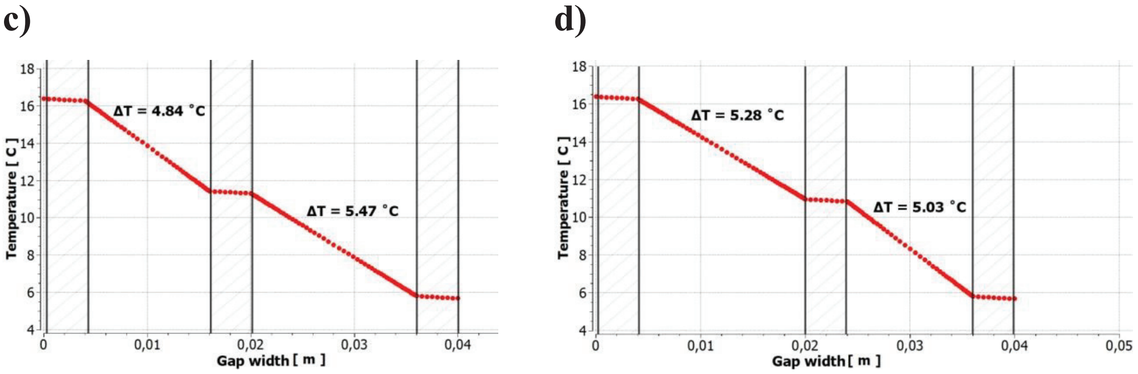


Figure 4.18. Temperature profiles of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=15°C for scenarios a, b, c, and d. (at y/H=0.5) (gap width 0 m is inside surface) (a) L_1–L_2 = 12-12 mm (b) L_1–L_2 = 16-16 mm (c) L_1–L_2 = 12-16 mm (d) L_1–L_2 = 16-12 mm

Variations of vertical velocity are represented by Figure 4.19 in the same conditions given in 4.17 and 4.18. The magnitudes of the velocities are decreased while comparing other scenarios because of the low temperature difference. As in all temperature ranges, the increase in the gap width has increased the velocity in this case.

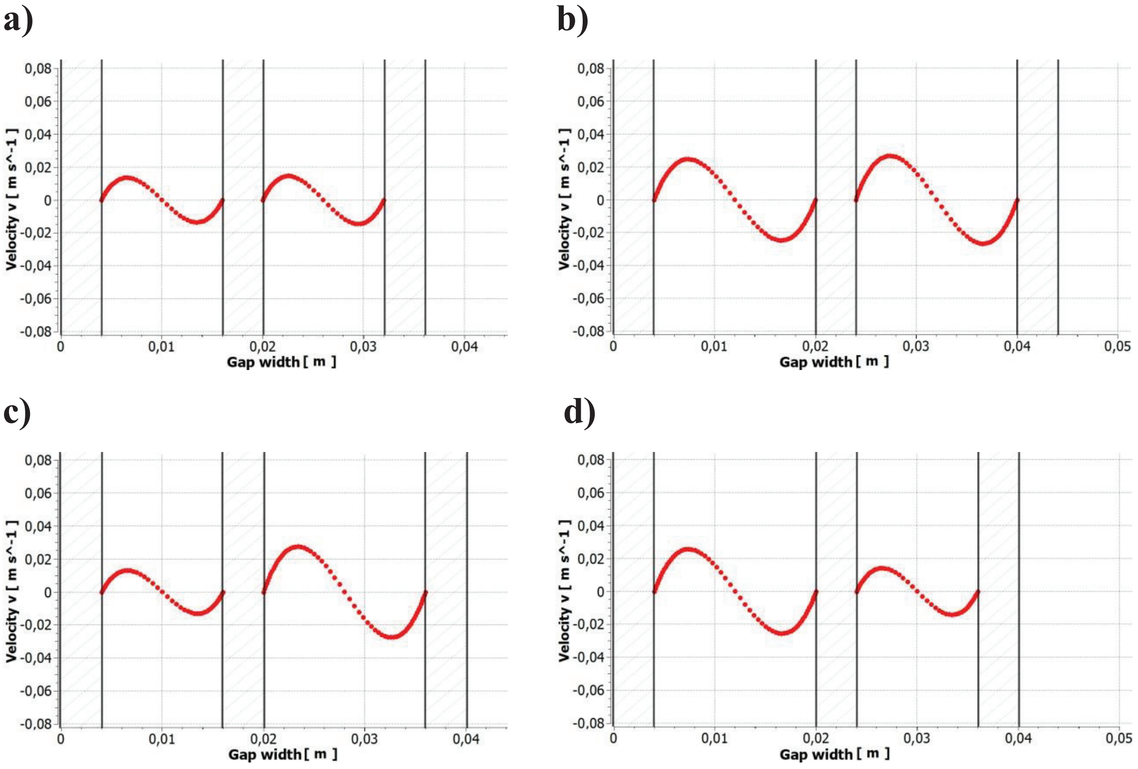


Figure 4.19. Velocity profiles of triple pane windows (Ɛ=0.84) due to gap widths at ΔT=15°C for scenarios a, b, c, and d. (at y/H=0.5) (gap width 0 m is inside surface) *(a)* L_1–L_2 = 12-12 mm (b) L_1–L_2 = 16-16 mm (c) L_1–L_2 = 12-16 mm (d) L_1–L_2 = 16-12 mm

4.6. The Effect of Using Low-e Coating Material on Heat Transfer

According to computation results, the U-value decreases when the emissivity of the glass pane decreases. It can be seen in the Figure 4.20. For instance; for the triple pane window having gap width $L_1 - L_2$ = 16 – 16 mm, U-value decreases from 1.86 to 0.92 W/m^{2}K when the emissivity of the surface is decreased from 0.84 to 0.1 at temperature difference is 15°C. And the reduction in the U-value is 51%. Although emissivity is reduced in the same condition, for the glazing systems having gap width L_1–L_2 = 12–12 mm, the reduction in the U-value is 46%. It is decreased from 1.97 to 1.07 W/m^{2}K. Because, the increase in the gap width decrease the heat transfer by conduction and convection but has no significant effect on the radiation heat transfer. Therefore, with the increasing gap width the effect of radiation on total heat transfer rate also increase. So, the reduction in the U-value is more definable with the reducing emissivity values at larger gap widths especially in the lower temperature difference.

Since the emissivity value decreases, the radiation heat transfer is reduced and that's why the effect of the U-value on the heat transfer increases.

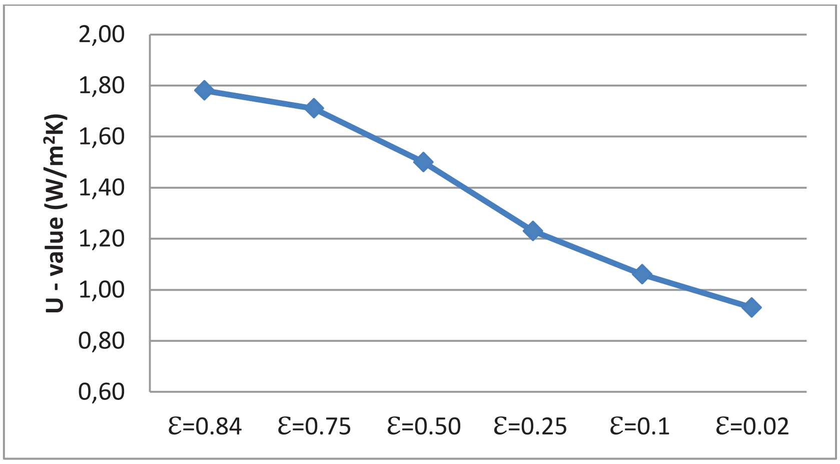


Figure 4.20. Variation of the U-value due to emissivity coatings on the glazing surfaces #2 and #5 when the gap widths are L1 – L2 = 16-16mm (ΔT=15°C)

With the emissivity coating of 0.1 on the glass surface #2 and #5 at the high temperature difference the scenario of 16 - 12 mm gap width gives the best result. So, for comparing with the glazing having 16 - 16 mm gap width, effect the emissivity variation on the U-value also investigated for the 16 - 12 mm cavity dimensions where the temperature difference is 48°C.

Table 4.4. Comparing U-value according to cavity width of the glazing system where the temperature difference is 48°C

Emissivity value - surface #2 and #5	U-value (W/m^{2}K)	
	L_1 - L_2 = 16 - 16 mm	L_1 - L_2 = 16 - 12 mm
Ɛ=0.84	1.78	1.80
Ɛ=0.75	1.71	1.73
Ɛ=0.50	1.50	1.51
Ɛ=0.25	1.23	1.24
Ɛ=0.10	1.06	1.05

Although the effect of radiation on total heat transfer in wide cavity dimensions is distinguished, the effect of convection on the total heat transfer is increased at the high temperature difference. Under these conditions, the effect of radiation decreases as the emissivity value decreases. For this reason, the temperature difference between glass panes also increases and higher velocities are seen in the cavity. Because of all these reasons, the effect of the convection heat transfer on the U-value increases and the gap width of 12 mm on the cold side gain importance for reducing the total heat transfer.

The velocity profiles of the glazing systems having 16 - 12 mm gap widths are shown by Figure 4.21 due to emissivity values when the outdoor temperature is -28°C.

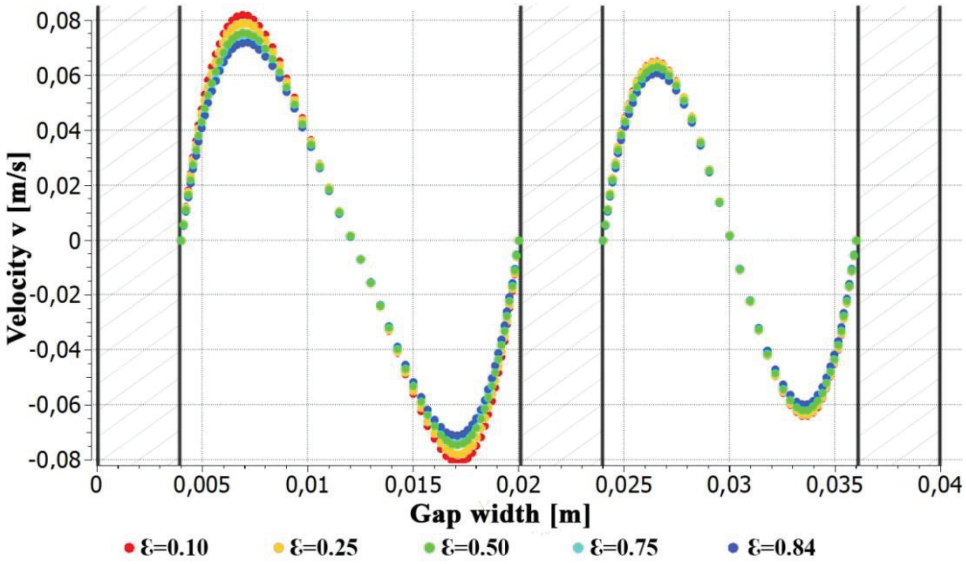


Figure 4.21. Velocity profiles of triple pane windows due to emissivity coatings on the glazing surfaces #2 and #5 when the gap widths are L1 – L2 = 16-12 mm (ΔT=48°C)

As can be seen from the Figure 4.21 when the emissivity value decreases, the velocity is increased in the gas filled cavity.

In a given scenario which is 16 – 12 mm gap width, a study was carried out on which glass surfaces the low-e coatings would be more effective. It is observed that the effects of emissivity coatings on the U-value are the same where coated on the 2nd and 5th surface or on the 3rd and 4th surface. However, it is not recommended to place the coatings on the middle glass. Because it can trap the heat between the glazing units and even may cause break the glazing units.[12] So, 2nd and 5th surfaces are determined for this study. In this way, heat loss from the inside can be reduced and external overheating can be prevented. When the low-e material coated on the all surface inside, the expecting reduction in the U-value is not realized. Therefore it is not preferred.

Table 4.5. Effect of the low-e coatings on the U-value on different glass surfaces

(ΔT=15°C) L_1 - L_2 = 16 - 12 mm	
(ε=0.1) Emissivity coating surface	U - value (W/m^{2}K)
#2, #3, #4 and #5	0.85
#2 and #5	0.99
#3 and #4	0.99

When the radiation excluded in the calculations, the calculated U values are physically meaningless. It is shown with the analysing of 12 – 12 mm and 16 – 16 mm gap widths scenarios including and excluding radiation heat transfer. The results are represented in the Table 4.6. This study shows the effect of radiation on the total heat transfer coefficient clearly.

Table 4.6. The effect of radiation heat transfer on the total heat transfer coefficient (ΔT=48°C)

L_1 - L_2 = 12mm		L_1 - L_2 = 16mm	
radiation (-)	radiation (+)	radiation (-)	radiation (+)
0.93	1.82	0.90	1.78

CHAPTER 5

CONCLUSION

This study was carried out in order to contribute to the determination of the appropriate window configuration according to the different cities which have different climatic conditions of Turkey. The main purpose of the study is to examine the thermal performance optimization of the windows according to various affecting parameters. For this purpose, the glazing part of the window has been analysed because of its low thermal resistance with the greatest effect on the thermal performance of the windows. For understanding the fluid flow and heat transfer problem, Computational Fluid Dynamics (CFD) modeling which is generally preferred in this research area was used. The glazing systems modeled in different gap widths were compared at different temperature differences due to the various emissivity values.

The heat transfer through the triple pane windows and the fluid flow in the cavity between the panes has been investigated. For this analysis, the most preferred two space widths were determined and combined in different ways which as 12 – 12 mm, 16 – 16 mm, 12 – 16 mm and 16 – 12 mm gap widths to be analysed. And emissivity values (0.1, 0.25, 0.5, 0.75 and 0.84) were taken for low-e coatings added to glass surfaces. When the outdoor temperatures were taken according to the average winter design temperature (-28°C, -17°C, -6°C, and +5°C) of cities (Ağrı, Sivas, Amasya and İskenderun) of Turkey, the indoor temperature was kept constant at +20°C. The external and internal convection coefficients were determined as 34 W/m^{2}K and 8.29 W/m^{2}K respectively. The cavity between the glass panes was filled with dry air and the characteristics of air were determined by the average temperature.

The density of the air, which significantly influences the fluid profile, was calculated by the ideal gas equation. The RNG k- Ɛ turbulence model that has been validated in the literature has been solved the fluid flow problem. The main result based on these parameters is the change in the total heat transfer coefficient (U-value) of the glass. The results can be summarized as follows:

- Increasing the gap width to a certain width reduces the amount of heat transfer rapidly, after 12 mm thickness of the cavity this decrease continues with a lower slope because of increasing natural convection in the cavity.

- The effect of the gap width on heat transfer is more noticeable in low temperature differences between inside and outside.
- When the analyses made with the standard glass at the same cavity widths are examined, the decrease in the temperature difference causes the average temperature to increase. This increases the U-value.
- In cases where heat transfer with radiation is not included in the calculations, the results are not accurate.
- Low-e material coating on glass surfaces significantly reduces the amount of heat transfer.
- The lower the emissivity value, the greater the effect of the gap width on the U-value.
- Increasing the width of the cavity reduces the heat transfer by conduction and convection up to a certain cavity width. However, it has no significant effect on radiation heat transfer. Therefore, as the gap width increases, the effect of radiation heat transfer on total heat transfer increases. So, to reduce the emissivity values of the surfaces at larger gap widths is more effective at reducing the U value.
- Due to the heat transfer by radiation, higher temperature differences and higher velocities are observed in the cavity at the cold side because of buoyancy forces.
- When the low-e coating reduces the effect of radiation on heat transfer, the main mechanism of heat transfer becomes convection. For this reason, suppressing natural convection and fluid velocity with high temperature difference can be achieved by using a gap width of 12 mm instead of 16 mm at the cold side. It is the scenario of gap width 16-12 mm.
- With using 16-12 mm gap width on the cold climate region it can be achieved optimum insulation without increasing the weight of the frame structure and the gap width.
- It has more advantages when the emissivity coating is on surfaces #2 and #5.
- Using 16-12 mm gap width in cold regions reduces heat transfer about 2% comparing to 12-12 gap width. And in warm climates, using 16-16 mm gap width reduces heat transfer 7% comparing to 16-12 mm.

This study showed that the optimum gap widths can vary with different temperature differences and outdoor temperatures. The studied configurations can be diversified considering the temperature differences in other cities of Turkey. 16-20 mm and 20-16 mm gap widths options can also be analysed. It will be useful to evaluate the glass and the frame together in future studies. In addition to these, the results of the study should be verified experimentally. Such detailed researches are prerequisites for being on the right lines in terms of energy conservation for the building sector.

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