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Effect of Thermal Barrier and Insulation Material Properties on Thermal Performance of the Windows Systems

Yigit Guller*, Dilara Birsen, Huseyin Gokdemir, Gokhan Ozer, Yasar Akca, Ebubekir Koc, and Metin Yılmaz

Cuhadaroglu Metal Sanayi ve Pazarlama A.S., Istanbul, Turkey Fatih Sultan Mehmet Vakif University, Aluminium Test Training and Research Center (ALUTEAM), TR 34445, Istanbul, Turkey

Abstract

Windows systems are the weakest points of buildings in terms of thermal performance. Most part of the windows systems contain glass with high thermal transmittance constant. The aluminum material is mostly deployed as a frame which has a very high thermal conductivity. In this study, the thermal transmission coefficient optimization studies of an aluminum frame system is carried out, furthermore of the Çuhadaroğlu DS90 windows system to increase the thermal performance of the system. The gaps between the thermal barriers which used to prevent the thermal conduction of the aluminum material, are filled with four different insulation materials, and their effects on the Uf value are investigated. For the aluminum window section, calculations carried out employing the FLIXO program considering the ISO 10077 standard. The results show that the best performances are achieved with Aerogel and phenolytic foam. The best Uf value of 0.87 W/ (m2.K) was obtained by optimizing the parameters of the gasket, frame-sash, and thermal barrier material (by considering the cost parameter) of the windows system.

Keywords: Windows systems; Thermal conductivity; Insulation materials; NZEB; Passive house

Introduction

The first law of thermodynamics, also known as energy conservation, states that energy cannot be created or destroyed; energy only transforms. According to the second law of thermodynamics, heat transfers from the high-temperature environment to the low-temperature environment if there is a temperature difference between the two environments. The heat transfer rate depends on the thermophysical properties of the heat transfer medium and the difference between ambient temperatures. Most energy loss in a standard window systems is due to the radiation transmitted through the glass. The glass cavity also adds to the total loss of a small amount of energy through convection. The air in the large glass spaces is heated by the inner glass, and the heated air rises and exchanges with cooler air. Thus, a convection current is produced in the system, which transfers the heat from the inner panel to the outer panel. The heat is transmitted through the window frame, and the rate of conduction depends on the frame material. Air leakage after radiation causes the most significant heat loss through existing windows systems. Heat is transmitted in three ways: conduction, convection, and radiation in the windows systems (Figure 1).

Conduction: It is the transmission of the energy passing from the particles in contact with each other from the high energy level to the low energy level between regions of an object at different temperatures. The energy transfer occurs because of the vibration of molecules in solid objects such as glass and frames. The rate of heat conduction through a medium depends on the medium's geometry, thickness, material, and temperature difference.

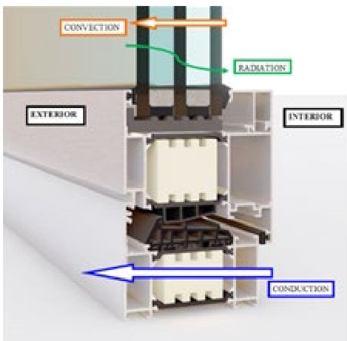

Figure 1: Heat transfer through a windows system (Çuhadaroğlu DS90 window system).

Convection is defined as If a fluid moves on a solid surface at a different temperature than the fluid; heat transfer occurs through convection. Convection heat transfer depends on fluid properties, flow rate, and temperature difference. Convection occurs between a different moving medium and the surrounding surface and is the heat transfer that occurs because of the movement of liquids or gases.

Radiation: Window surfaces emit thermal radiation in all directions. The amount of heat transfer by radiation depends on the surface's temperature, emission values , and appearance factors [1-4].

The most widely exploited energy in the world depended upon fossil fuels. Some of the heat energy required to provide the desired internal temperature in the indoor environment of the building is provided from internal sources and solar energy. The heating systems must provide the excess amount to the indoor environment. This causes extra energy loss and consumption [5]. Energy-based studies are carried out in many different sectors against the depletion of resource reserves. The construction industry is one of them. The systems where the most energy losses occurs in buildings are exterior cladding systems. There are several studies are presented on glass units

***Corresponding author:** Yigit Guller, Cuhadaroglu Metal Sanayi ve Pazarlama A.S., Istanbul, Turkey Fatih Sultan Mehmet Vakif University, Aluminium Test Training and Research Center (ALUTEAM), TR 34445, Istanbul, Turkey, E-mail: yigit_guller@cuhadaroglu.com

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since their relatively great size in the whole system and the total heat transfer coefficient. However, window frames should be considered as important as the glass units with less heat loss since their high heat transfer. Aluminum, which is highly preferred in the sector as a frame material, creates further complications that need to be addressed in energy-saving implementations since its high thermal transmittance [6-11].

Thermal insulation is defined as the necessary process to reduce the heat transfer between two environments at different temperature states to prevent the formation of any thermal bridges. It is essential to reduce the energy we spend to make indoor environments warm or cool enough in the related seasons with the least possible cost [12,13].

Legal Obligations

A significant part of the energy we use in our world is met from exhaustible sources such as coal, natural gas, oil, and nuclear (see Figure 2). The exploitation of these resources is considered mostly harmful to the environment [14,15]. As can be seen in the Figure 3, building ranks as the second highest in the energy consumption in the world. The energy consumption in buildings is higher in many developed and developing countries compared to their populations and therefore more energy is needed. In recent years saving at the energy source has come to focus with the renewable energy. Although this has started under companies' leadership, it has been legally enforced by the governments in recent years [16].

Many legal initiatives are presented by states on energy efficiency have reached international levels today. One of the very first initiatives is the Kyoto protocol, which was voluntarily signed by many states on 11 December 1997 on the fight against global warming and climate change. International agreements and legal sanctions such as the green deal, the Paris agreement, and the Glasgow agreement have been signed by many states on climate and environment [17]. These agreements dictate the necessity of reducing their energy consumption, including in buildings, and implementing to more environmentally friendly methods.

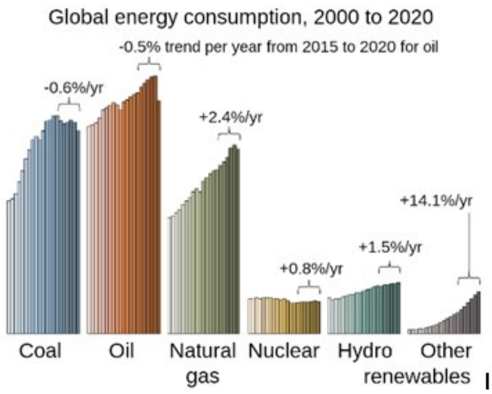

Figure 2: Primary energy sources consumed in the world.

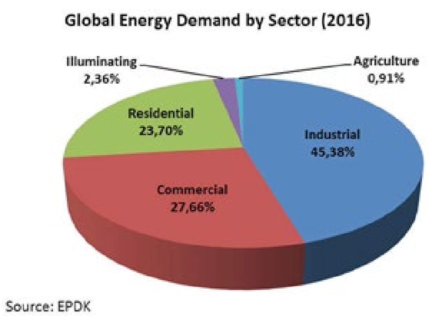

Figure 3: Global energy demand by sectors.

To address the global warming trend from greenhouse emissions, the European Union (EU) has been involved in developing strategies to mitigate the adverse effects of climate change. The construction industry is responsible for approximately 40% of the energy needed in the "Energy Performance in Buildings Directive" declared by the EU parliament in 2002. It aims to improve energy performance and reduce energy consumption and environmental impact. Many studies have shown how a reduction in primary energy consumption, CO_2 gas emissions and cost reductions can be achieved to obtain highly efficient buildings. The studies present a methodology based on comparing various energy efficiency measures to identify the most cost-effective solutions for buildings in a warmer climate. Building performances are also being investigated in cold regions such as Estonia, the United States, and China [18].

The Kyoto Protocol was adopted at the conference in Kyoto in 1997 to challenge global warming and climate change and entered into force in 2005. The aim is to reduce carbon dioxide emissions and energy consumption in the atmosphere. In 2002, inspired by the Kyoto Protocol, the EU directive on the energy performance of buildings (EPBD) was published and rearranged in 2010 (European Energy Performance of Buildings 2010/ 31/EU). In addition, the published directive emphasized the importance of the "Near Zero Energy Buildings (NZEB)" project. NZEB is defined as creating buildings with zero or very low energy consumption. All the buildings in EU member states will be built as "Zero Energy" before 31 December 2020 according to these initiatives. In 1988, the Passive House Standard was prepared by scientists in Germany. The Passive House is not an energy standard but an integrated concept that provides the highest comfort level. Following this concept, 90% energy savings are achieved compared to standard structures. The energy consumed for heating and cooling in passive houses is 15 (kWh) kilowatt hours per square meter at most. Since 2019, European Union countries have been working on the necessary laws, regulations, and standards to ensure that all buildings comply with the Passive House standard.

In Turkey, several key implementations have been made in the energy performance regulation in buildings. The current regulation entered into force on 19 February 2022. The definition of "Near Zero Energy Building (NZEB): A building with high energy performance and at the same time a certain amount of renewable energy use" has been added to the regulation.

Materials and Methods

Even the smallest improvements in the construction industry provide significant gains in total energy consumption in buildings with a life span of at least 30 years. There are several studies have been presented on window materials and systems with efficiency calculations. The window's thermal performance depends on the frame's thermal and geometric properties and interaction between the components. Window frames are modeled according to the international EN ISO 10077-2 standards. Heat transfer in the frame is a combination of conduction in solid materials and convection and radiation in air-filled spaces. However, the frame cavities are considered solid materials with equivalent thermal conductivity representing the heat flow to simplify the calculations.

Architectural systems use finite element analysis programs to detect weak points in thermal transmittance during the design phase. Therm, Bisco, Window, Flixo, and FrameSimulator are some of the examples of these programs which are frequently used by experts. Thus, it is possible to improve the thermal performance at the design stage. The thermal transmittance calculations made in this study was made with FLIXO finite element analysis program. The thermal conductivity of air spaces can be calculated automatically according to the TS EN ISO 10077-2 standard by the FLIXO. To calculate the thermal transmittance of the frame section, an insulating panel with thermal conductivity of λ= 0.035 W/mK replaces the opaque panel in bg thickness of existing glass. The insulated panel bg length must be greater than 190 mm, and the height equal to 1000 mm (Figure 4). The panel's surface is considered an adiabatic boundary. The dimensions to be considered in the thermal transmittance of the architectural system can be seen in Figure 4. The calculation cannot be performed if the specified dimensions are lower than the given values in Figure 4.

Thermal Optimization Strategies

These three strategies are achieved by frame optimization to reduce the thermal conductivity coefficient.

The first strategy is to increase the width of the frame material and create the maximum number of closed chambers during the design of the plan/section detail of the aluminum frame material.

The second strategy is to choose the insulation barrier material used to prevent heat conduction with a low thermal conductivity coefficient and to keep the barrier as high as possible since aluminum has a high thermal conductivity coefficient.

The third strategy is to fill the gaps between the barriers with insulation materials with a low thermal conductivity coefficient to reduce the convection effect of air through the window.

Optimization work should also be carried out on the EPDM gasket, which is highly preferred in the industry for air and water tightness used between aluminum window profiles. The number of chambers and decrease between the gasket and the thermal barrier is necessary. Although the EPDM materials already provide a low thermal conductivity, a two-component gasket is being used to further reduce the heat coefficient.

While EPDM material is used to provide strength in the area that provides sealing with the contact of the gasket to the thermal barrier, the EPDM foam material is preferred in areas that do not need strength.

According to ISO and CEN standards, if the material's thermal conductivity value (λ- lambda) is less than 0.065 W/m.K, thus, it can be called a thermal insulation material according to ISO and CEN standards. If it is higher than this value, it is then called a building material. The thermal conductivity values of the insulation materials used for this study are shown in Table 1.

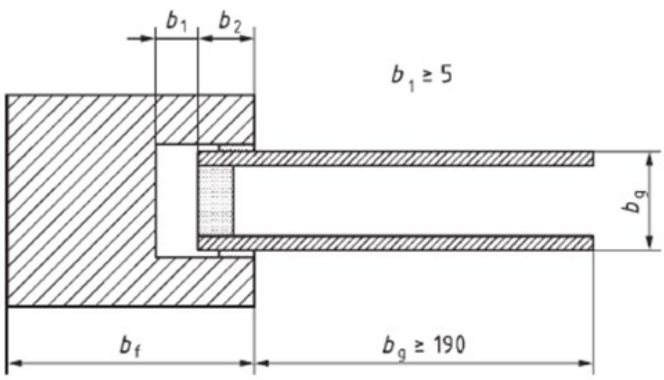

Figure 4: Measures to be considered in thermal transmittance.

The study examines the effect of U_f (Thermal transmittance of the frame) on the insulation materials by considering the third strategy. U_f value can be improved by optimizing several parameters in the window section detail. Only some parameters were kept constant to examine the insulation material's effect, which are;

- The height of the heat barrier is 54mm,
- Narrow Frame and sash
- The width of the insulation panel is 36mm

Phenolic foam is a closed-cell rigid foam containing phenolic resin and other additives. Phenolic foam is the best insulation material due to its excellent fire resistance performance, low smoke emission, high-temperature resistance, stability, superior thermal performance, and extremely robust insulation property. The operating temperature range of the foam is -180°C - +180°C (Table 2) .

Polyurethane is produced from two materials, isocyanate and polyol, obtained from crude oil. Polyurethane foam shows good thermal properties. The operating temperature range is –200°C to +135°C (Table 2). The average thermal conductivity coefficient of polyurethane foam is 0.025 W/m.K. The most significant advantage of polyurethane foam is its excellent thermal insulation properties. Due to this feature, one of the most frequently preferred materials for all kinds of construction and renovation works, such as welded assembly and sealing. The disadvantages of the material are its relative flammability and low resistance to UV radiation.

When the best insulation material for a climate zone is investigated according to the minimum life cycle cost and initial cost recovery time criteria; Although the aerogel insulation material has a higher initial cost, the initial cost recovery time of Aerogel insulated walls in a colder climate was found to be less than three years due to its high heat resistance properties. Although the initial cost is high, it can be classified as an economically beneficial type of material [19].

Table 1: Lambda coefficient of materials used in the simulations.

Materials	Thermal conductivity λ(W/m.K)
Aluminum	160
Polyamide (PA66GF25)	0.3
Low lambda polyamide (LLPA66GF25)	0.21
Phenolic foam	0.023
Polyethylene foam (PE)	0.049
Polyurethane foam (PU)	0.025
Aerogel	0.014
Insulation panel	0.035
EPDM	0.25
EPDM foam	0.06

Table 2: Material properties of Phenolic, Polyethylene foam .

Value	Phenolic foam	Polyethylene foam	Polyurethane foam	Aerogel
Density (kg/m³)	56	40	70	20 – 120
Durability	-180 to +180°C	-100 to +80°C	-200 to +135°C	-180 to +180°C
Specific heat (J/kgK)	-	-	1,500	990

Experimental Studies

Insulation panels are deployed to calculate the thermal transmittance of the frame. It is calculated only by heat conduction through the frame without using glass (Equation 1.1). This calculation method is carried out with a low heat transmission coefficient panel. The panel, as mentioned earlier, heat transfer coefficient is 0.035 W/m.K. While the calculated U_f value includes only the heat transmission coefficient of the aluminum profile frame, no information or results are obtained regarding the interaction of any parameter related to glazing, such as the spacer.

$$U_f = \frac{L_f^{2d} - U_p b_p}{b_f} \quad (1.1)$$

where;

U_f: Thermal transmittance of aluminum profile frame [W/m².K]

L_f: Thermal conductivity of the Frame

U_p: Thermal transmittance of the central area of the insulation panel [W/m².K]

b_p: Width of insulation panel [m]

b_f: Width of Frame [m]

Results and Discussion

The effect of the insulation materials used on the thermal transmittance value of the aluminum frame can be seen in Figure 5.

The best results was obtained by filling the empty space between the thermal barriers with insulation material using aerogel insulation material. The thermal transmittance value decreases to 1.91 W/m²K. A decent improvement is observed in the U_f value, as the thermal transmittance value of the aerogel material is lower than that of all other insulation materials used. The thermal transmittance value is 1.93 W/m²K using a Phenolytic insulation board may be considered as another good material after Aerogel. In the insulation materials benchmark, the worst material observed as Polyethylene, with a thermal transmittance of 1.98 W/m²K.

The thermal transmittance value obtained from the polyethylene foam extrusion piece placed under the glass only in the window frame section without using insulation material between the thermal barriers is 2.02 W/m²K, which has little effect on U_f. Another parameter that should be considered to meet the desired thermal transmittance value in the window frame is the thermal barriers used as an insulation bridge to the aluminum profile. The heat transmission coefficient of the Polyamide (25% glass fiber reinforced) material used as thermal barriers is 0.3 W/m.K. The heat transmission coefficient of low lambda thermal barriers is 0.21 W/m.K [20,21]. The parameters to be considered during the design phase are the material from which the thermal barrier is produced and the width value.

In this study Polyamide (glass fiber reinforced 25%) material is chosen. Polyamide material is widely used in architectural systems since its production as extruded profile, its mechanical properties like aluminum, and especially its low heat transmission coefficient. Even better conditions are provided by the low lambda PA66 material, which has been preferred in recent years. In this study, the insulation panel was kept constant at 36mm, and narrow frame-sash parameters and three measurements were determined to examine only the thermal barrier width parameter. These are 34, 44, and 54 mm. Two different materials were deployed as thermal barrier materials. These are LLPA (low lambda polyamide) and PA (polyamide). Figure 6 shows the effect of thermal barrier width and material parameters on Uf. According to the result, the U_f value gives better results with LLPA, which has a low heat conduction coefficient value. As seen in Figure 6, the thermal barrier width parameter gives better results as the material width increases.

As a result of all these parameter studies, the U_f value of 0.87 W/m2.K was obtained with the optimization study of Çuhadaroğlu company's DS90 window system (Figure 7). This value makes the window system proves to be in the range of the Passive House concept according to recent standards.

Conclusions

A benchmark study of the U_f value was carried by deploying four different aluminum window frame insulation materials. As a result of this study, the insulation material aerogel is proves to be better material in the benchmark results. In terms of cost and examining all

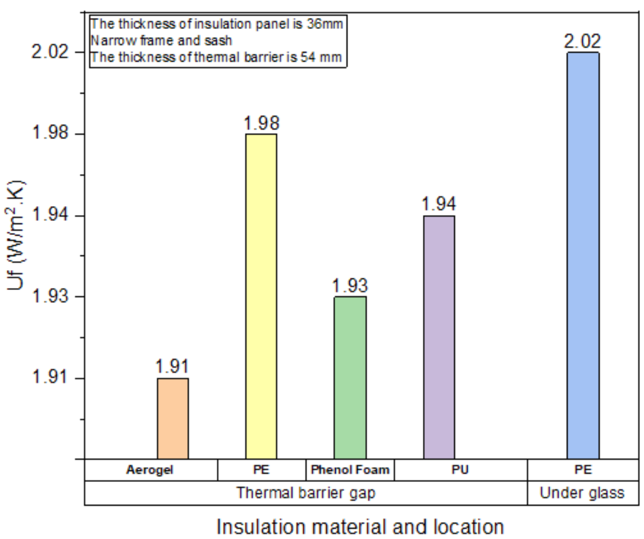

Figure 5: The effect of the insulation material filled into the cavity on the U_f value.

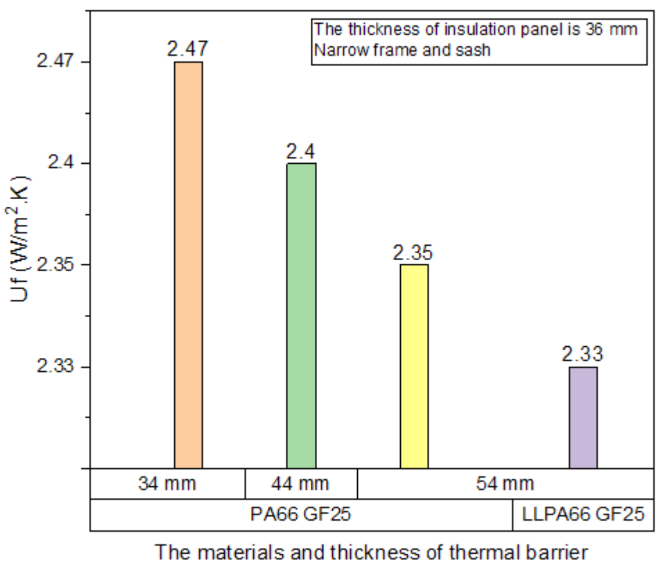

Figure 6: The effect of thermal barrier material and width of barrier on U_f value.

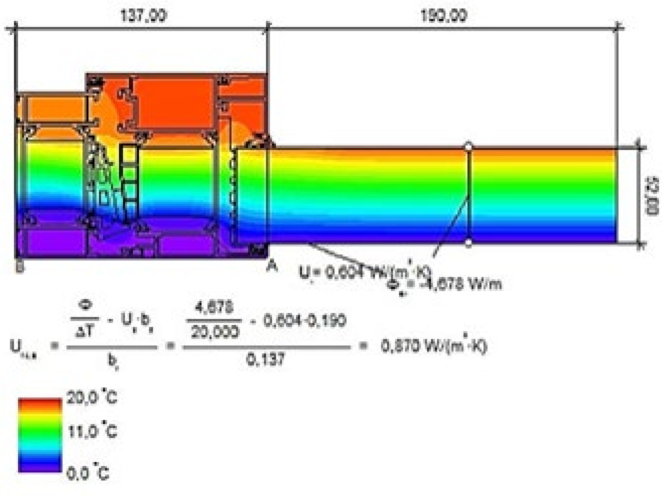

Figure 7: Flixo working image of Çuhadaroğlu DS90 window system compatible with passive house certificate.

other possibilities, more than one parameter is determined to improve the Uf value. Optimum results have been obtained by changing several parameters; the geometry of the gasket and the ability to produce the gasket with two-components material the material and height of the thermal barrier, the insulation material used to fill the barriers, and the width of the window.

The aforementioned parameter has a positive effect on the thermal transmission coefficient. Although the best insulation material is Aerogel, it has a higher manufacturing cost. However, there is a significant improvement in thermal conduction by using phenolytic foam or polyurethane foam materials.

Novel opportunities and significant new workload arise for many sectors after increase in the amount of energy used and obligations imposed by the states. This study will guide the window manufacturers to comply with the requirements and minimize energy costs. As a result of the optimization study of the DS90 the Çuhadaroğlu windows system, a value of 0.87 W/(m2K) was obtained with the most feasible combination, considering the cost and energy loss parameters. With this data, the window system compatible with the passive house certificate has been incorporated into their structure, and a window complying with the NZEB requirement is obtained.

As a result of this study, the parameters that affect the thermal conductivity performance in the best way are;

• Aerogel as insulation material,

• The width of the thermal barrier is 54 mm,

• The material of thermal barrier is low lambda PA66,

• As the cross-sectional area of the aluminum profile increases, the thermal transmittance value also decreases. The reason for the decrease in thermal transmittance as stated in Equation (1.1), as the frame width bf increases, the thermal transmittance value U_f value decreases.

• The use of a two-component gasket.

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