ZEROBUILD JOURNAL

Araştırma Makalesi

Türel ve ark. 02:01 (2024) 99-114

İnfiltrasyon Kayıplarının Bina Enerji Performansına Etkilerinin İncelenmesi Üzerine Deneysel Bir Yaklaşım

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Öne Çıkanlar:
- Sızıntı büyüklüğüne ilişkin deneysel bir çalışma geliştirildi
- Tek pencereden saatlik enerji kaybı 1,95 kWh'a kadar çıkabilir
- Tek pencereden toplam ısıl güç kaybı 0,54 kW'a kadar çıkabilir
- Pencerelerden hava kaçağı nedeniyle sızma kaybı %17'den fazla olabilir.

Geliş Tarihi: 04.01.2024 Kabul Tarihi: 20.01.2024 Doi: 10.5281/zenodo.10565245

Amaç:
Bu çalışma, farklı pencere tipleri, cepheler ve konumların sızdırmazlık değerlerinin belirlenmesi ve hava sızıntısı enerji kayıplarının hesaplanması için bir yaklaşım geliştirilmesi amaçlanmıştır.

Metot:
Yalova ve Kocaeli'ndeki sekiz farklı pencerede yapılan deneylerle, infiltrasyon kayıplarının farklı cephelerde konumlanan pencereler üzerindeki etkisi belirlenmek üzere analitik hesaplar yapılmıştır. Çalışmada 10 nokta ölçüm metodu geliştirilmiş ve kullanılmıştır. 10 nokta ölçüm metodunda bütün pencerelerden aynı 10 nokta ölçülerek değerlendirme yapılmıştır.
Deneyler, özellikle pencerelerin çerçeve birleşim noktaları, contalar ve diğer potansiyel sızıntı bölgelerindeki mikro boyuttaki aralıklardan kaynaklanan hava sızıntısının hızını belirlemek amacıyla uygulanan bir dizi ölçümü içermektedir.

Sonuçlar:
Çalışma, pencerelerden 6,3 m/s'ye kadar ulaşan sızma hızının, odadan 1,95 kWh'lik kayda değer bir termal enerji kaybına yol açtığını ortaya çıkardı. Rüzgâr karşılayan odalar ile rüzgarın yönüne göre binanın arkasında konumlanan odalar arasında sızma kayıplarında kayda değer bir fark tespit edildi. Arka tarafta kalan odalarda daha düşük sızma kayıpları görülürken, rüzgarı karşılayan odalarda yaklaşık %20 oranında daha yüksek kayıplar yaşandı. Bu fark, rüzgar yönü ile sızma kayıpları arasında önemli bir korelasyon olduğunu vurgulamaktadır. Sızma kayıplarının cephelerin yönünden daha fazla açıklığın büyüklüğünden etkilendiği görülmüştür. Sorunlu pencerelerdeki açıklıkları en aza indirmek ve yalıtımı geliştirmek, binalardaki enerji kayıplarının azaltılmasına önemli ölçüde katkıda bulunabilir.

Anahtar Kelimeler: İnfiltrasyon, sızdırmazlık, hava sızıntısı, doğrama tipi, sıfır enerji, conta ve montaj kusurları, enerji performansı

ZEROBUILD JOURNAL

Research Article

Turel et al. 02:01 (2024) 99-114

An Experimental Approach to Investigate the Effects of Infiltration Losses on Building Energy Performance

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Highlights:

- An experimental study on the infiltration magnitude is developed
- The hourly energy loss from a single window can be up to 1.95 kWh
- Total thermal power loss from a single window may be up to 0.54 kW
- The infiltration loss because of air leakage from the windows may be more than %17

Received: 24.01.2024 Accepted: 20.01.2024 Doi: 10.5281/zenodo.10565245

Abstract

The substantial impact of energy losses, potentially reaching up to 20% due to infiltration around windows, necessitates in-depth research. To address this issue, experiments were conducted on eight different windows across three distinct buildings in Yalova, Turkey. Buildings in Turkey are constructed in accordance with TS 825 standard. The buildings examined are also built in accordance with the same legislation. They do not have any features in terms of energy performance.

The primary objective was to investigate the effects of leaks in various types of windows positioned on different facades and orientations. A 10-point measurement method, developed as part of this study, was utilized to identify air leakage characteristics in micro-gaps at the frame joints, gaskets, and other potential leakage areas of windows. Subsequently, the magnitude of leakage was calculated, and the causes of leakage were examined. The highest measured infiltration rate in the experiments was 6.3 m/s, estimating a total thermal energy loss of 1.95 kWh in a selected window. This research seeks to offer valuable insights into understanding and mitigating the impact of infiltration on building energy performance.

Keywords: Infiltration, airtightness, air leakage, window type, zero energy, gasket and assembly defects, energy performance

1. Introduction

Windows are an indispensable element in our homes for receiving natural light, ventilation, and windows are essential to let in natural light, ventilation and connect inside with the outside world. However, the air-tightness of windows is often overlooked and infiltration can lead to both energy loss and comfort problems.

Sealing windows is essential to improve the energy efficiency of the home, prevent heat loss and ensure thermal comfort inside. Turkey is an energy importer country. From 1990 to 2010, primary energy demand increased from 53 TOE to 109 TOE [1]. Considering that 70% of the energy demand is met by imports, the importance of energy saving becomes evident. Energy consumption of buildings accounts for approximately 34% of total energy consumption in Turkey [2]. The first step towards reducing this ratio can be seen as the Thermal Insulation Regulation for Buildings (TS 825), which entered into force in 2000 [3]. This step was followed by the "Regulation on Energy Performance in Buildings (BEP)" published on 12.05.2009 and energy efficiency studies gained momentum [4].

Buildings are responsible for 36% of global energy consumption and 37% of CO2 emissions [5]. Throughout the world, practices for the efficient use of energy in buildings are developed and encouraged, and many organizations operate for this purpose [6]. Zero Energy Buildings stand out as non-energy consuming buildings that can be located in any geography and climate conditions. With appropriate planning, Zero Energy Buildings can achieve energy savings in the design phase, resulting in substantial reductions in energy bills and carbon emissions. This economic advantage presents a valuable opportunity, benefiting not only the occupants of such buildings but also contributing to the overall energy efficiency goals of nations [6].

Although heat losses in buildings vary according to the architectural design and condition of the building, it is generally stated that 30% of the total heat loss for a multi-storey house is caused by windows and 17% by air leaks, while 20% of the total heat for a single-storey house is caused by windows and 13% by air leaks [7]. Since windows have higher U-values compared to other building elements, they are responsible for about 47% of the total energy loss through the building envelope [8–10]. Infiltration losses account for about 20% of the total heat loss even in temperate climates [11].

Air tightness is an important performance parameter for windows and the average energy efficiency and indoor comfort conditions of dwellings are strongly influenced by the degree of tightness of windows.

The air infiltration of a window is contingent upon various parameters, including wind strength, direction, and design and quality factors. Micro-sized gaps in window sashes and seals play a significant role in influencing air infiltration. Simultaneously, minor gaps between the window frame and the wall, resulting from imprecise installation; permit the movement of air between indoor and outdoor environments [12].

The growing interest in energy conservation and building airtightness is leading to more research on the design and implementation of airtight components, e.g. wall-to-frame joints [11], joints materials [13-14] and using wind barriers to achieve airtightness [15]. There is also a growing interest in estimating the overall airtightness of buildings on the basis of qualitative assessment [16–18].

In the literature, studies have generally focused on energy losses from buildings, addressing issues such as insulation, the heat transfer coefficient of windows, and thermal bridges. However, there is a lack of satisfactory research specifically addressing leakage losses. This article presents an experimental study that will provide crucial data for research on leakage losses. What makes this article unique is the inclusion of experimental data obtained from windows in different buildings, window types, and orientations. While the energy loss calculation is an approximation and may not be considered precisely accurate, it is crucial as a foundational aspect for future studies in this field.

Table 1. Window characteristics of Building and Dormitory Windows

Window Frame Type	Glass Type	Glass Thickness	Façade Direction	Date	Time
PVC1	Double Glazing	12mm	NW	12.11.2023	12.00
PVC2	Double Glazing	12mm	W	12.04.2023	00.50
PVC3	Double Glazing	12mm	E	12.11.2023	23.10
AL-1	Double Glazing	18mm	SE	12.11.2023	14.30

Table 2. Window characteristics of Yalova University Faculty of Engineering

Window Frame Type	Glass Type	Façade Direction	Date	Time
AL-D302	Double Glazing	265° W	12.13.2023	15.19
AL-D301	Double Glazing	3° N	12.13.2023	15.32
AL-D309	Double Glazing	156° SE	12.13.2023	16.46
AL-D312	Double Glazing	70° E	12.13.2023	16.51

2. Material and Method

Measurements were conducted on a total of eight different windows, using a hot wire anemometer to observe the leakage of various window types, facades, and locations. Among these buildings are three residential structures, one dormitory, and the Yalova University Faculty of Engineering building. Information regarding these windows is provided in Table 1 and Table 2.

At Yalova University Faculty of Engineering, experiments were conducted to investigate the influence of simultaneously placing windows on different facades, each subjected to the same wind load, on infiltration losses. The codes assigned to the windows for measurements were determined according to their respective classrooms, with each window situated on a distinct facade of the building.

Throughout the study, a 10-point measurement method was employed to all experiments to investigate the impact of air leakage from windows.

Figure 1. 10-Point Measurement Method

In tables, W represents the West, N represents the North, SE represents the Southeast, and E represents the East facade.

2.1 10-Point Measurement Method:

In this study, a 10-Point Measurement Method has been developed to determine air leaks around the windows. In the 10-Point method, measurements were taken using a hot wire anemometer, and infiltration rates were measured from ten different points around the windows corresponding to the same location on each window. This method provides standardization for determining air leaks in ten regions around the window. With this method, the speeds of air leakage through micro-sized gaps that may occur at the window frame joints, gaskets, and other potential leakage areas are determined. The identified 10 points represent the areas where the highest leakage occurs. Figure 1 proposes the locations of the 10 points around the window, which were identified in the experiments to standardize the regions where leakage is most intense. The window seen in Figure 1, comprises one fixed and one movable window sash. Some windows may not have a fixed sash. In such cases, measurements will not be taken at points 6 and 7.

2.2 Measurement Device

The measurements are performed with hotwire anemometer. The specifications of the device employed in the experiments are given in Table 3.

2.3 Detection of Leakage Area

Area measurements were conducted employing custom-produced feeler gauges specifically designed for this research. The inflexible structure of steel feeler gauges, commonly utilized in the automotive industry, rendered them unsuitable for window frame measurements due to limited space. Consequently, a flexible type of feeler gauge, comprising various types of paper, was developed in this study to establish a standard unit thickness.

Table 3. Specifications of the hotwire measurement device

Make and Model	Metravi AVM-10 Hot Wire Anemometer
Measures	Air velocity and Temperature
Velocity Measuring Sensor	Glass Bead Thermisstor
Temperature Measuring Sensor	Precision Thermisstor
Measure	Low velocity of Air
Air Velocity Range	0.1 to 25.0 m/s
Accuracy	± 5%
Temperature Range	0°C to 50°C
Accuracy	± 1%

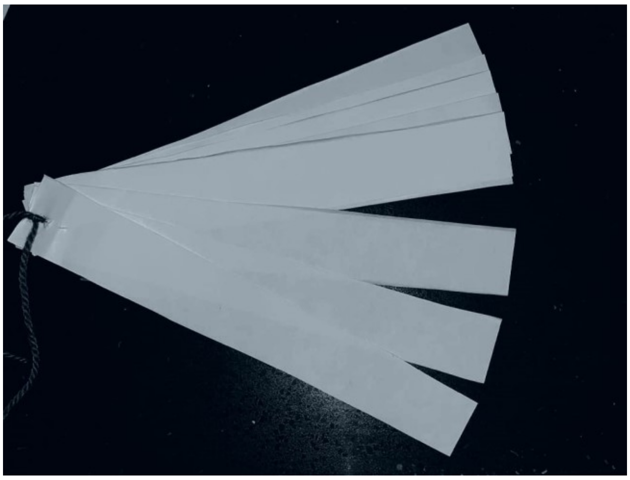

Figure 2. Paper feeler gauges

The average thickness of the paper gauges used in the measurements was calculated using Equation 1.

$$t_0 = \sum_{i=0}^{n} \frac{t_i}{n}$$

The gauge used in the measurements was placed flat and single-layered without being compressed into the gaps at the window edges. The thickness of the paper, which entered the gap without folding, was calculated to determine the area of the leakage. The mass flow rate of the leakage passing through the gap was calculated using Equation (2).

$$\dot{m} = \rho . V . A$$

Here, the mass flow rate of air is expressed as $\dot{m}$ (kg/s), the density of air expressed as ρ (kg/m^3), the infiltration area expressed as A (m^2) and the infiltration rate expressed as V (m/s). The thermal losses, assuming that the entire mass of air infiltrated is heated to the indoor air temperature, have been calculated using Equation (3).

$$\dot{Q} = \dot{m} . C_p . (T_i - T_o)$$

Here, the thermal power loss $\dot{Q}$ is in (kW), the specific heat of air Cp is in (kJ/kg·°C), and the temperature difference between the indoor and outdoor environments (T_i–T_o) is in °C.

3. Results and Discussion

In this study, the energy lost via infiltration caused by micro-gaps around windows and the impacts of facades on this energy loss were investigated. The wall-frame junction, hinge, and gasket issues of the measured windows are illustrated in Figure 3.

In the PVC1 experiment, the indoor air temperature of an apartment on the top floor of a three-story residence in Yalova was measured at 18.6°C, while the outside air temperature was recorded as 13°C (Table 4). Additionally, the wind speed is 7 m/s to the Northwest direction.

In Figure 4, the maximum amount of energy loss is observed at measurement point 4. Point 4 causes more significant losses than other points due to the width of the leakage area. 36.2% of the total lost energy occurs at point 4 for PVC1 window. The cause of the infiltration in this region is determined as gasket deformation.

In the PVC2 experiment Table 5, the indoor air temperature of an apartment on the top floor of a four-storey residence was measured at 23.4°C, while the outside air temperature was recorded as 21.3°C. Additionally, the wind speed is 5 m/s and the direction is North.

In Figure 5, the maximum energy loss is observed $4.69x10^{-1}$ kWh at measurement point 4. The next highest energy consumption is $3.22x10^{-1}$ kWh at point 9. These two points constitute 46.61% of the total energy consumption.

In the PVC3 experiment, the indoor air temperature of the apartment on the second floor of a five-story building in Yalova was measured 21.4°C, while the outside air temperature was recorded 8.7°C (Table 6). Additionally, the wind speed is 8.5 m/s, from the East. The experiments showed that the max infiltration speed in the school building can be up to 4.5 m/s.

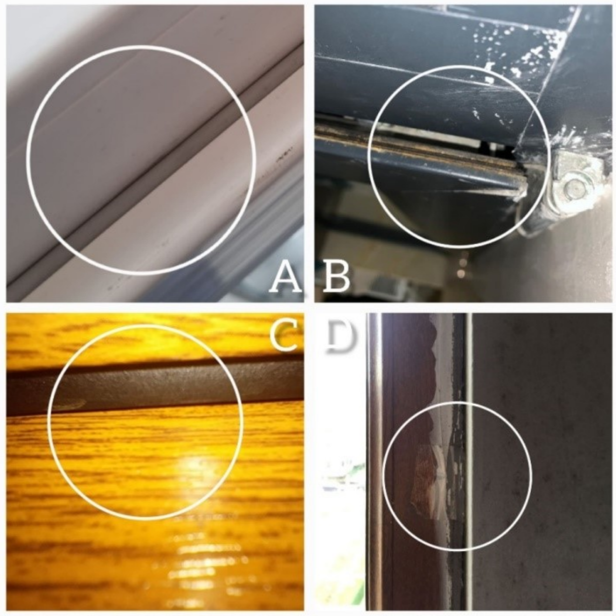

Figure 3. Connection issues in windows: A PVC2, B AL-1, C PVC1, D PVC3

Table 4. PVC1 Experiment Results

PVC1	Inf. Speed (m/s)	Area (m^2)	$\dot{m}$ (kg/s)	$\dot{Q}$ (kW)
1. Point	3.67	$1.00x10^{-6}$	$4.50x10^{-6}$	$2.53x10^{-5}$
2. Point	3.79	$5.00x10^{-7}$	$2.32x10^{-6}$	$1.31x10^{-5}$
3. Point	4.10	$1.00x10^{-6}$	$5.02x10^{-6}$	$2.83x10^{-5}$
4. Point	4.13	$3.50x10^{-6}$	$1.77x10^{-5}$	$9.97x10^{-5}$
5. Point	3.98	$5.00x10^{-7}$	$2.44x10^{-6}$	$1.37x10^{-5}$
6. Point	4.12	$5.00x10^{-7}$	$2.52x10^{-6}$	$1.42x10^{-5}$
7. Point	3.76	$5.00x10^{-7}$	$2.30x10^{-6}$	$1.30x10^{-5}$
8. Point	3.64	$5.00x10^{-7}$	$2.23x10^{-6}$	$1.25x10^{-5}$
9. Point	3.64	$1.50x10^{-6}$	$6.69x10^{-6}$	$3.70x10^{-5}$
10.Point	3.87	$5.00x10^{-7}$	$2.37x10^{-6}$	$1.31x10^{-5}$

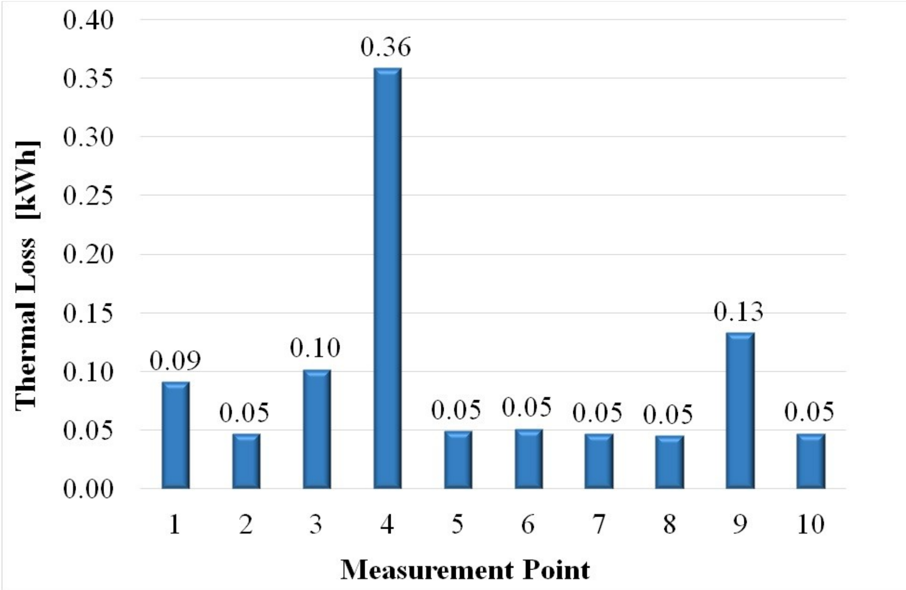

Figure 4. Infiltration loss around window PVC1

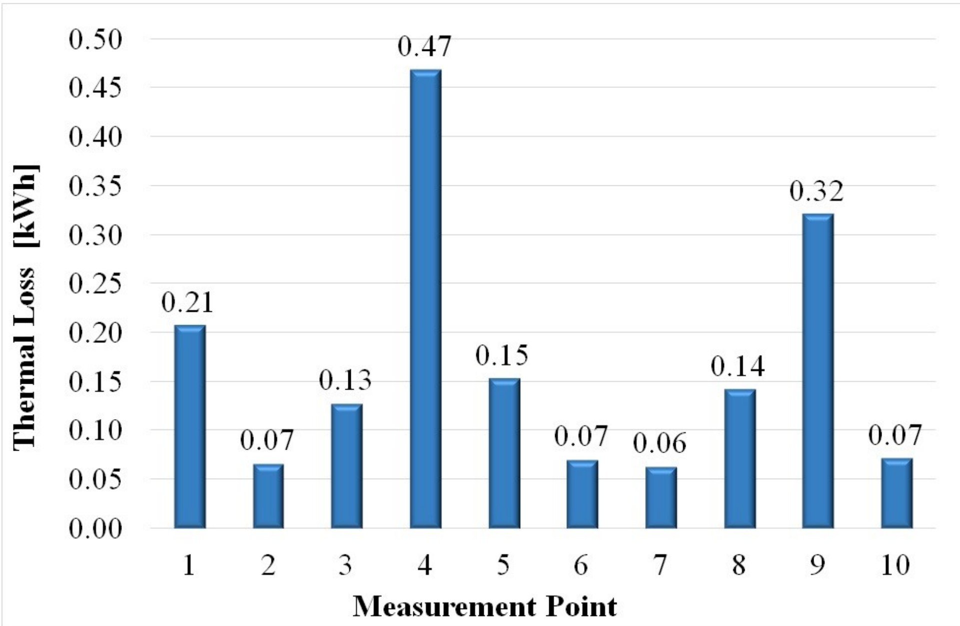

Figure 5. Infiltration loss around window PVC2

In Figure 6, the maximum amount of lost energy is observed at measurement point 9 and point 6 follows as the second-highest. These two points constitute 35.55% of the total energy losses. The reason for the maximum energy loss at point 9 is the failure of the opening wing of the window to fit into the frame and the deformation of the gasket between the window frame and the casing.

In the AL1experiment, the indoor air temperature of a room on the fifth floor of a five-story dormitory in Yalova was measured 24.3°C, while the outside air temperature was 13.4°C (Table 7). The wind speed is 8 m/s, coming from the Northeast.

Table 5. PVC2 Experiment Results

PVC2	Inf. Speed (m/s)	Area (m^2)	$\dot{m}$ (kg/s)	$\dot{Q}$ (kW)
1. Point	4.12	6.00×10^{-6}	3.03×10^{-5}	5.78×10^{-5}
2. Point	4.18	2.00×10^{-6}	1.02×10^{-5}	1.85×10^{-5}
3. Point	4.02	4.00×10^{-6}	1.97×10^{-5}	3.56×10^{-5}
4. Point	4.64	1.20×10^{-5}	6.82×10^{-5}	1.30×10^{-4}
5. Point	4.57	4.00×10^{-6}	2.24×10^{-5}	4.28×10^{-5}
6. Point	4.44	2.00×10^{-6}	1.09×10^{-5}	1.97×10^{-5}
7. Point	4.01	2.00×10^{-6}	9.82×10^{-6}	1.78×10^{-5}
8. Point	4.24	4.00×10^{-6}	2.08×10^{-5}	3.97×10^{-5}
9. Point	4.32	8.00×10^{-6}	4.23×10^{-5}	8.94×10^{-5}
10.Point	4.29	2.00×10^{-6}	1.05×10^{-5}	2.01×10^{-5}

Table 6. PVC3 Experiment Results

PVC3	Inf. Speed (m/s)	Area (m^2)	$\dot{m}$ (kg/s)	$\dot{Q}$ (kW)
1. Point	3.88	1.50×10^{-6}	3.68×10^{-6}	4.62×10^{-5}
2. Point	3.82	5.00×10^{-7}	1.23×10^{-6}	1.51×10^{-5}
3. Point	4.17	1.00×10^{-6}	2.45×10^{-6}	2.95×10^{-5}
4. Point	4.3	1.00×10^{-6}	2.45×10^{-6}	2.93×10^{-5}
5. Point	4.15	5.00×10^{-7}	1.23×10^{-6}	1.48×10^{-5}
6. Point	4.26	2.00×10^{-6}	4.90×10^{-6}	6.01×10^{-5}
7. Point	3.77	1.00×10^{-6}	2.45×10^{-6}	3.03×10^{-5}
8. Point	3.94	1.50×10^{-6}	3.68×10^{-6}	4.58×10^{-5}
9. Point	4.47	2.00×10^{-6}	4.90×10^{-6}	6.50×10^{-5}
10. Point	3.93	5.00×10^{-7}	1.23×10^{-6}	1.58×10^{-5}

Table 7. AL1Experiment Results

AL-1	Inf. Speed (m/s)	Area (m^2)	$\dot{m}$ (kg/s)	$\dot{Q}$ (kW)
1. Point	6.3	2.20×10^{-6}	1.70×10^{-5}	1.35×10^{-4}
2. Point	5.24	1.00×10^{-6}	6.42×10^{-6}	5.94×10^{-5}
3. Point	4.31	1.00×10^{-6}	5.28×10^{-6}	5.09×10^{-5}
4. Point	5.59	7.00×10^{-7}	4.79×10^{-6}	4.77×10^{-5}
5. Point	4.43	4.00×10^{-7}	2.17×10^{-6}	2.23×10^{-5}
6. Point	4.42	1.00×10^{-7}	5.41×10^{-7}	6.20×10^{-6}
7. Point	5.94	1.00×10^{-7}	7.28×10^{-7}	8.78×10^{-6}
8. Point	5.5	4.00×10^{-7}	2.70×10^{-6}	2.95×10^{-5}
9. Point	5.03	2.20×10^{-6}	1.36×10^{-5}	1.51×10^{-4}
10.Point	5.79	4.00×10^{-7}	2.84×10^{-6}	3.02×10^{-5}

In Figure 7, the highest energy loss occurs at measurement point 9, while Table 6 reveals the highest infiltration rate at measurement point 1. This distinction distinguishes the AL1 experiment from others. The differentiation arises from the larger area of the micro-gap at point 9 compared to point 1. Point 9 exhibits the greatest energy loss, succeeded by point 1. Together, these two points account for 52.87% of the total energy lost through this window. Air leakage in AL1 double-opening window is attributed to hinges not fully seating during the closing process and the wear of gaskets. During the experiments conducted at Yalova University Faculty of Engineering, the assessment of window energy loss centered on the prevailing wind direction, a pivotal factor influencing energy efficiency.

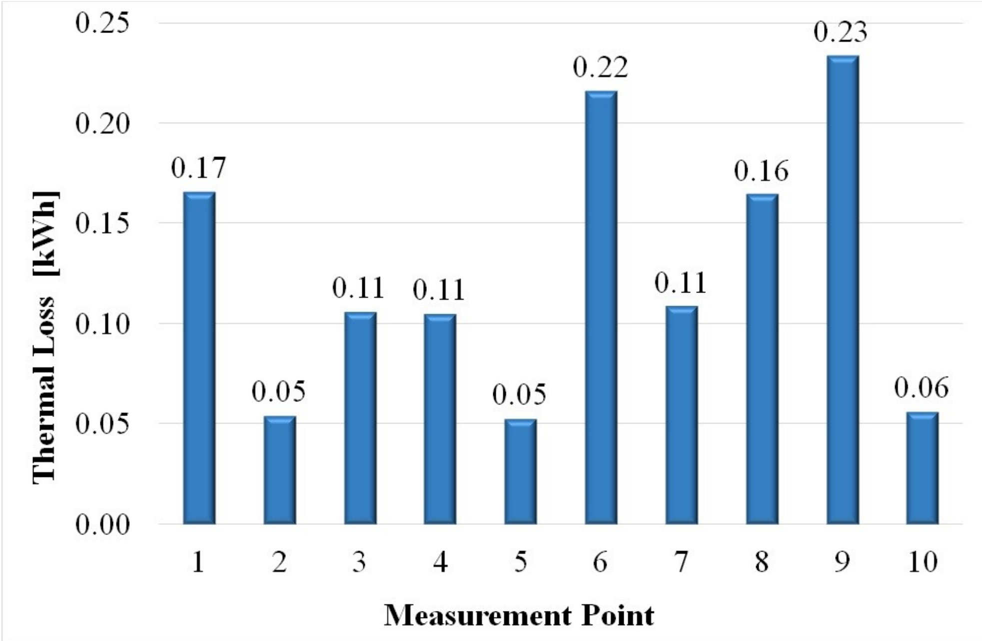

Figure 6. Infiltration loss around window PVC3

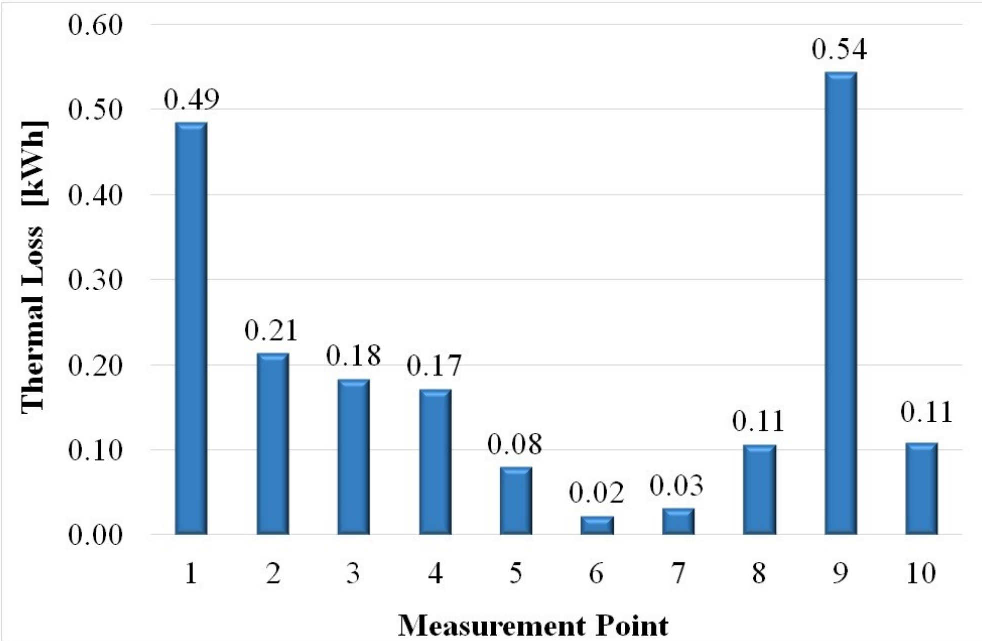

Figure 7. Infiltration loss around window AL1

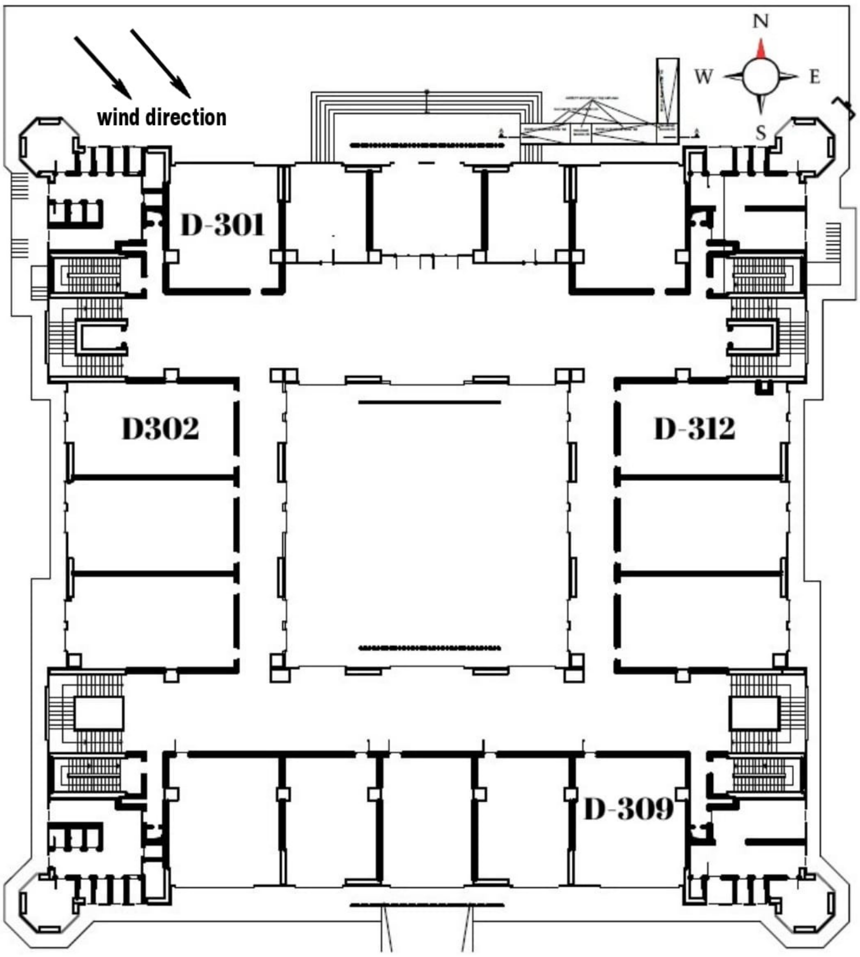

Figure 8. Floor Plan of Yalova University Engineering Faculty Building and Wind Direction (Northwest)

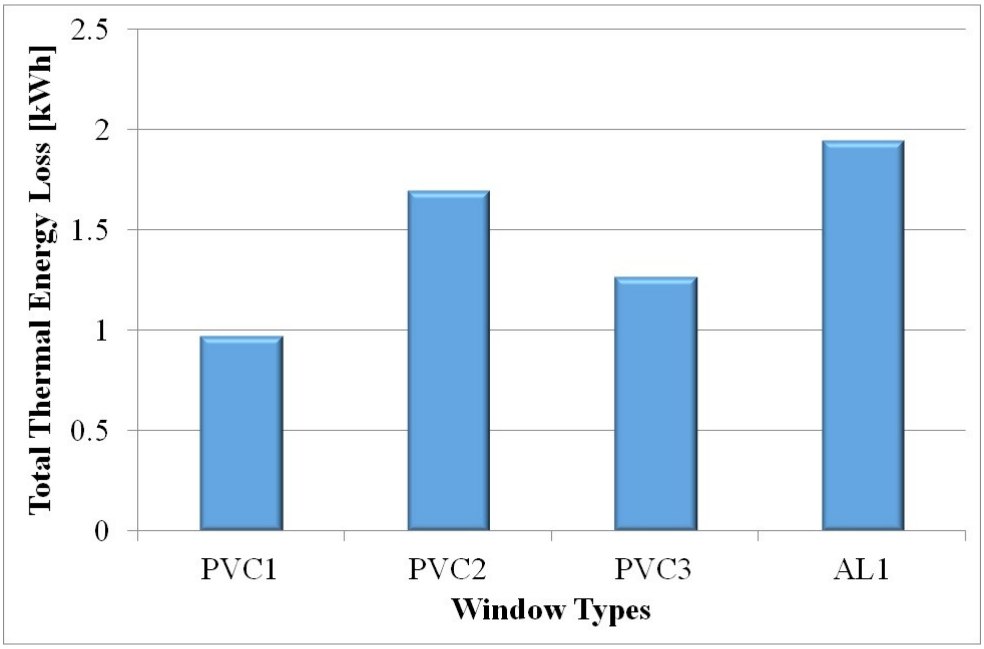

Figure 9. Comparison of all windows

In Figure 9, a comparison of total energy losses among various window types is illustrated. Notably, the data implies that the aluminum window type exhibits the highest propensity for energy loss. However, caution should warranted against drawing conclusive judgments solely based on a single experimental result. Rather, it can be said that the collective data underscores the potential for infiltration losses from a window to ascend up to 2 kW.

Experiments (AL_D301, AL_D302, AL_D309, and AL_D312) were conducted on the second floor of Yalova University's Engineering Faculty, with each classroom situated in a different cardinal direction (Figure 8). Specifically, AL-D301 faces the North, AL-D302 is on the West, AL-D309 is oriented to the South, and AL-D312 is on the East side of the building. The primary objective of these experiments conducted in these varied locations was to assess and compare the impact of both room positioning and wind direction. The outside temperature was measured 12°C and wind speed was measured 7 m/s originating from the South. The room temperatures of the classrooms AL-D302, AL-D301, AL-D309, and AL-D312 were recorded 21.1°C, 19.2°C, 19.6°C, and 20.9°C respectively. The measured infiltrations are given in detail in Table 8. The widest air leak was observed in measurement point 2 at AL-D301.

Table 8. AL-D302 Experiment Results

Room No	Measurement Point	Infiltration Speed (m/s)	Area(m^2)	$\dot{m}$(kg/s)	$\dot{Q}$(kW)
AL-D302 (N)	1	5.68	2.00x10^{-6}	1.39x10^{-5}	1.27x10^{-4}
	2	4.71	1.00x10^{-6}	5.77x10^{-6}	5.2810x^{-5}
	3	4.51	2.00x10^{-6}	1.10x^{-5}	9.99x10^{-5}
AL-D301 (W)	1	4.54	2.00x10^{-6}	1.11x10^{-5}	7.60x10^{-5}
	2	4.29	7.00x10^{-6}	3.68x10^{-5}	2.59x10^{-4}
	3	5.44	2.00x10^{-6}	1.33x10^{-5}	9.64x10^{-5}
	4	5.07	1.00x10^{-6}	6.21x10^{-6}	4.56x10^{-5}
	5	4.38	1.00x10^{-6}	5.37x10^{-6}	4.04x10^{-5}
	6	3.87	6.00x10^{-6}	2.84x10^{-5}	2.20x10^{-4}
AL-D309 (S)	1	4.12	1.00x10^{-6}	5.05x10^{-6}	3.70x10^{-5}
	2	4.5	5.00x10^{-6}	2.76x10^{-5}	2.05x10^{-4}
	3	4.02	1.00x10^{-6}	4.92x10^{-6}	3.76x10^{-5}
	4	4.24	1.00x10^{-6}	5.19x10^{-6}	4.07x10^{-5}
	5	4.21	1.00x10^{-6}	5.16x10^{-6}	4.04x10^{-5}
	6	3.92	2.00x10^{-6}	9.60x10^{-6}	7.63x10^{-5}
AL-D312 (E)	1	4.58	1.00x10^{-6}	5.611x10^{-6}	4.736x10^{-5}
	2	5.59	1.00x10^{-6}	6.848x10^{-6}	5.987x10^{-5}
	3	4.53	1.00x10^{-6}	5.549x10^{-6}	5.019x10^{-5}
	4	5.1	1.00x10^{-6}	6.248x10^{-6}	5.651x10^{-5}
	5	3.97	1.00x10^{-6}	4.863x10^{-6}	4.350x10^{-5}
	6	4.14	1.00x10^{-6}	5.072x10^{-6}	4.536x10^{-5}

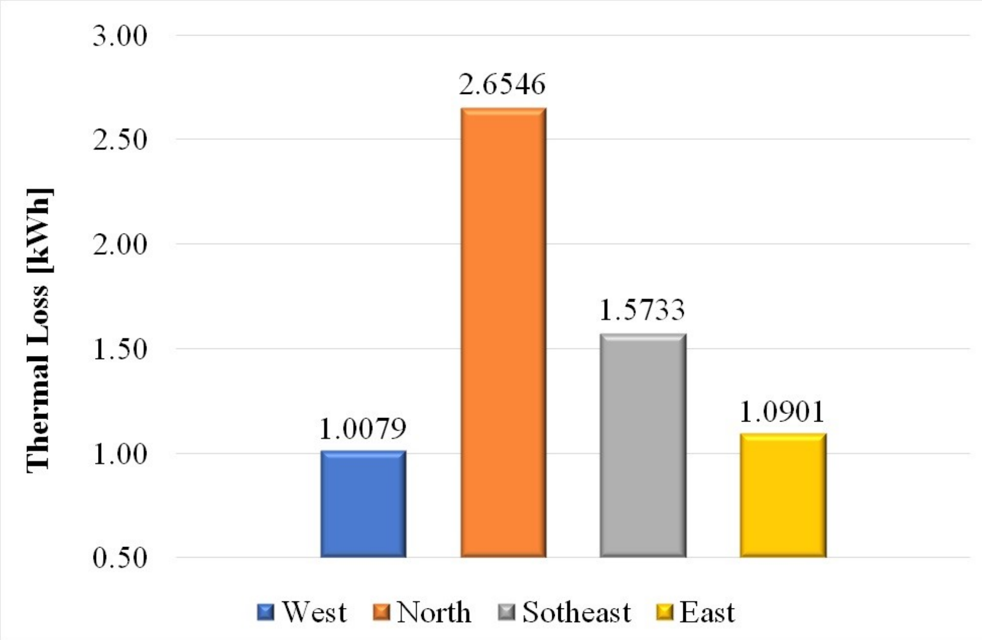

Figure 10. Energy Loss According to Facades

In the experiments, the highest infiltration rate was measured in the north-facing AL-D302 window, perpendicular to the wind direction, with a maximum of 5.68 m/s and an average of 4.97 m/s. The east-facing AL-D312 recorded an average of 4.60 m/s, while the west-facing AL-D301 showed an average of 4.65 m/s. In the room facing away from the wind direction, AL-D309, the lowest infiltration average was measured at 4.17 m/s. These results indicate that infiltration in rooms facing the wind direction can be up to 20% higher. For more reliable results, it is recommended to repeat the experiment on days with different wind speeds and wind directions.

Figure 10 illustrates the air tightness performance of windows on different facades of the Faculty of Engineering at Yalova University. The experiment indicates that energy losses are most pronounced on the North facade, followed sequentially by the Southeast, East, and West facades.

Living things have basic needs such as perceiving their environment, seeing light, breathing fresh air and interacting with nature. Windows are wall spaces created to meet these needs [19]. The uncontrolled flow of air into the interior through window joints or various gaps is called "infiltration" [20]. Air leakage through windows is an important factor in determining the heating and cooling needs in a building [21-22]. Air leakage varies depending on wind speed and the temperature difference between inside and outside. This unwanted air flow adversely affects the comfort conditions in the space and increases the loads of heating and cooling systems. The amount of air leakage depends on climatic conditions, wind conditions and air movements around the building [23]. Air leakage is most common at the joints of window systems. Wall-frame joints, frame-sash joints and glass joinery joints are potential areas for air passage [23]. Air tightness in windows can be ensured by correct detailing and application. According to the RAL (German Quality Association for Plastic Window Systems) guidelines, the warranty period for window and installation seals (sealing gasket) is 6 months, which means that window seals must be replaced every year [24]. Joining areas should be filled with air-tight elastic filling and supported with materials such as gaskets and seals. In addition, the details of moving areas such as the frame-wing should be designed to prevent air passage. Windows in the main living spaces should be oriented to the south to maximize daylight and solar heat gain [25]. Increasing the window area on the south façade increases thermal gains and infiltration. Minimizing the window area on the north façade will reduce thermal losses [25].

4. Concluding Remarks

Infiltration Rate and Thermal Energy Loss:

- The study revealed a noteworthy infiltration rate at windows, reaching up to 6.3 m/s, resulting in a consequential thermal energy loss of 1.95 kWh from the room.

Wind Direction Impact:

- In regions where the prevailing wind direction is north, it was observed that infiltration losses are more influenced by the size of the opening rather than the facades.
- The study underscores the critical role of the opening size, revealing that an opening problem in leaking windows can amplify energy loss by up to 2 kWh in a specific location, irrespective of the building's orientation.

Wind-Facing Rooms vs. Opposite Wind Rooms:

- A notable disparity in infiltration losses was identified between rooms facing the wind and those positioned opposite to it.
- Rooms oriented toward the wind exhibited lower infiltration losses, while rooms opposite to the wind experienced comparatively higher losses.
- This observed ratio approximates 20%, highlighting a significant correlation between wind direction and infiltration losses in the examined scenarios.

Practical Implications:

- These findings emphasize the practical implications of addressing window-related infiltration issues for enhancing overall energy efficiency.
- Implementing targeted solutions to minimize openings and enhance insulation in problematic windows could contribute substantially to mitigating energy losses in buildings.

Future Research Considerations:

- The study raises avenues for future research, urging a deeper exploration of specific design modifications and technological interventions aimed at minimizing infiltration losses in diverse environmental and architectural contexts.

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