

## THERMAL PERFORMANCE AND HEAT FLUX DYNAMICS OF ELECTRICALLY HEATED WINDOWS: A FOUNDATION FOR ENERGY-EFFICIENT ACTIVE GLAZING SYSTEMS

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**Abstract.** The building sector remains a primary contributor to global energy consumption, with windows often identified as the least efficient component of the building envelope. This study investigates the thermal performance of an “active” smart window system featuring an integrated electrical heating element within the glazing cavity. Experimental trials were conducted in a specialised dual-zone climatic chamber to evaluate the heat flux dynamics and surface temperature distributions of a heated triple-glazed unit (TGU) compared to a standard reference unit. High-precision thin-film heat flux sensors and calibrated thermocouples were utilised to quantify thermal transfer across an external temperature range of  $-25\text{ }^{\circ}\text{C}$  to  $+5\text{ }^{\circ}\text{C}$ . The results demonstrate that precise modulation of the heating power enables the achievement of a “near-zero thermal balance,” effectively transforming the window from a thermal bridge into a thermally neutral element. While active heating elevates the external glass surface temperature, leading to increased external heat dissipation, it simultaneously mitigates the “cold pane” effect and enhances indoor radiant comfort. The findings suggest that the positive thermal effect on the indoor environment can outweigh external losses, particularly when managed as a demand-responsive system. The study concludes that integrating active glazing with renewable energy technologies, such as semi-transparent photovoltaics, offers a viable pathway toward achieving Net Zero Energy Building (NZEB) standards by providing a self-powering, high-performance architectural solution.

**Keywords:** active glazing, electrically heated windows, heat flux density, thermal comfort, energy efficiency, smart buildings, net-zero thermal balance, NZEB.

### 1. Introduction

The building sector currently accounts for approximately 40% of global energy consumption and remains a primary contributor to greenhouse gas emissions (Liu et al., 2025). Indoor environmental quality, specifically the maintenance of a stable thermal and moisture regime, depends heavily on the complex interaction between heating, ventilation, and air conditioning (HVAC) systems and the insulation capacity of the building envelope (Jia et al., 2021). The temperature distribution within a heated space is shaped by aerodynamic and heat exchange processes that facilitate thermal transfer from appliances to the external environment through the building’s structural components (Basok et al., 2021, 2022). Within this envelope, windows are traditionally considered the “weakest link” due to their inherently low thermal resistance and static optical properties (Jørgensen & Ma, 2025; Hafnaoui et al., 2024). An effective strategy for mitigating these losses is the replacement of legacy glazing with modern, energy-efficient triple-glazed units. Low-emissivity coatings are specifically engineered to

address the radiative component of heat transfer by selectively permitting short-wave solar radiation to enter the interior while reflecting long-wave thermal radiation back into the room (Amirkhani et al., 2019; Al-Shatnawi et al., 2024). This mechanism significantly reduces the energy required to maintain thermal comfort. Beyond radiative losses, researchers have focused on the conductive component of heat transfer; filling TGU cavities with inert gases, such as argon or krypton, effectively suppresses conduction (Michael et al., 2023; Jelle & Gustavsen, 2010). However, even with advanced coatings and gas fillings, condensation remains a prevalent issue, particularly if the hermetic sealing is compromised or environmental conditions are extreme (Duan et al., 2021; Cho et al., 2023).

To overcome these limitations, recent innovations have moved beyond passive solutions towards “active” smart windows. These systems integrate internal energy sources within the glazing cavity or onto the glass surfaces, potentially enhancing energy-conserving characteristics by up to 20% and reducing overall heating costs

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by approximately 10% (Basok et al., 2024). Electrically heated windows, in particular, have gained traction as a high-performance solution (Kurnitski et al., 2004). While active heating may slightly increase the local heat flux through the glass, it allows for the minimisation of the temperature differential between the indoor air and the window surface, thereby eliminating the “cold window” effect and significantly enhancing occupant radiant comfort (Lee et al., 2022).

It is important to note, however, that active window heating leads to an increase in heat flux through the glass pane. Yet, the minimisation of the temperature gradient between the room and the window surface helps lower the aggregate heat loss of the structure. The purpose of this work was to analyse the thermal behaviour of a triple-glazed unit with an integrated inter-pane energy source and to provide an efficiency assessment of such heated glazing.

## 2. Materials and methods

### 2.1. Experimental setup

The experimental investigations were performed using a specialised dual-zone climatic chamber located at the Laboratory of Energy-Efficient Technologies, Kielce University of Technology (Figure 1). This environmental chamber is specifically engineered to replicate precise indoor and outdoor conditions through the rigorous regulation of air temperature and relative humidity.



Figure 1. The dual-zone climatic chamber located at the Laboratory of Energy-Efficient Technologies

The chamber is divided into two functional compartments. The left-hand “indoor” section is a mobile unit configured to simulate internal building environments; it allows for temperature adjustments ranging from  $-5\text{ }^{\circ}\text{C}$  to  $+50\text{ }^{\circ}\text{C}$  and relative humidity levels spanning from 10% to 98%. Conversely, the right-hand “outdoor” section is a stationary compartment designed to emulate external meteorological conditions. This zone operates within a broader temperature range of  $-30\text{ }^{\circ}\text{C}$  to  $+80\text{ }^{\circ}\text{C}$  and maintains humidity control between 10% and 98%. Furthermore, the exterior section is equipped

with advanced simulation systems to replicate additional environmental stressors, including wind, precipitation, enabling a comprehensive assessment of the glazing unit’s performance under diverse climatic scenarios. In this study, the wind simulation system was utilized to maintain stable convective conditions, allowing for an assessment of the system’s thermal stability under forced airflow.

To evaluate the thermal performance and energy efficiency of active glazing, two identical window units were mounted between the chambers: a test unit equipped with an integrated electric heating element and a standard (reference) unit without heating. The glazing configuration for both units consisted of a triple-glazed assembly with a 16 mm gas-filled gap ( $L = 16\text{ mm}$ ) and a low-emissivity coating ( $\varepsilon = 0.17$ ). The active window was modified by installing a self-adhesive PE heating foil (Conrad Electronic, Hirschau, Germany) within the glazing cavity. This 210 W heating element (nominal dimensions  $350 \times 600\text{ mm}$ ) was powered at 230 V. Thermal regulation was managed by an H-Tronic TSM 12 temperature switch and controller (H-Tronic GmbH, Hirschau, Germany), which modulated the operation of the foil based on specific surface temperature setpoints. The measurements were performed simultaneously for both windows under identical boundary conditions to ensure a rigorous comparative analysis.

### 2.2. Instrumentation and data acquisition

The monitoring system was designed to record temperature distributions and heat flux densities across the internal and external surfaces of the glazing (Figure 2).

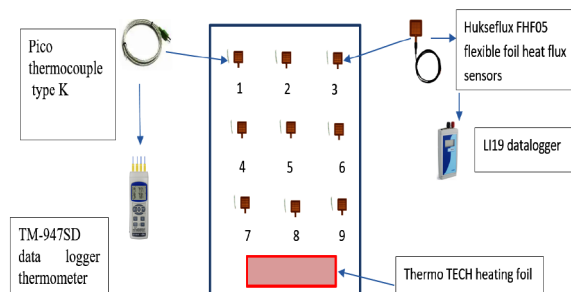


Figure 2. Schematic layout of the monitoring and heating system, featuring Hukseflux FHF05 flexible heat flux sensors, Pico thermocouples, and Thermo TECH heating foil

Internal and external surface temperatures, as well as temperatures within the glazing cavities, were monitored using calibrated thermocouples with an operating range of  $-40$  to  $+1000\text{ }^{\circ}\text{C}$  and a measurement accuracy of  $\pm 1.5\text{ }^{\circ}\text{C}$ . These were connected to a four-channel digital thermometer (TM-947SD, Lutron, TMS Europe Ltd., Bradwell, UK) featuring a data-logging resolution of 0.1. Heat flux densities, encompassing conductive, radiative, and convective heat transfer components, were

monitored using nine FHF05 thin-film flexible heat flux sensors (Hukseflux, Delft, Netherlands). These sensors are specifically designed for applications requiring high thermal sensitivity and flexibility, allowing for seamless integration with the glass surfaces. The sensors possess a nominal sensitivity of approximately  $20 \mu\text{V}/(\text{W}/\text{m}^2)$  and are capable of operating within a broad temperature range from  $-70 \text{ }^\circ\text{C}$  to  $+120 \text{ }^\circ\text{C}$ . The acquired signals were processed using an LI19 high-precision data logger (Hukseflux, Beijing, China), which recorded minimum, maximum, and instantaneous mean values with a measurement uncertainty of less than 0.1%.

### 2.3. Boundary conditions and experimental procedure

The experiments were conducted under stabilised microclimatic conditions. The indoor (left) chamber was maintained at a constant temperature ( $T$ ) of  $20 \text{ }^\circ\text{C}$  with a relative humidity of 50%. The outdoor (right) chamber temperatures were varied incrementally from  $-25 \text{ }^\circ\text{C}$  to  $+5 \text{ }^\circ\text{C}$  in steps of  $5 \text{ }^\circ\text{C}$ . The data collection process commenced only after the system reached a steady-state thermal regime. The acquired datasets were subsequently utilised for a comparative energy performance assessment between the heated and non-heated glazing systems.

## 3. Results and discussion

### 3.1. Heat flux distribution and thermal balance

The experimental results concerning the heat flux density distribution are illustrated in Figure 3. To ensure a comprehensive analysis of the thermal behavior across the entire glazing surface, measurements were conducted at nine distinct points, as indicated in the schematic layout (Figure 2). These data, captured using high-sensitivity Hukseflux FHF05 thin-film sensors and a dedicated LI19 heat flow logger, facilitate a precise quantitative comparison of the thermal dynamics across the monitored areas.

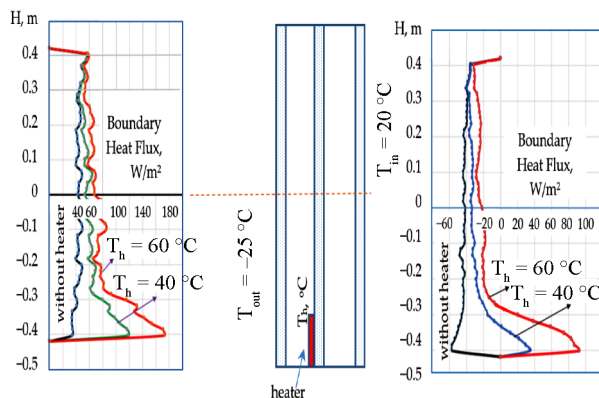


Figure 3. Heat flux density distribution at points 1–9 for the characterisation of the active glazing system’s thermal behaviour

As shown in Figure 3, the activation of the electric heating element significantly alters the traditional thermal behaviour of the glazing. At an external ambient temperature of  $0 \text{ }^\circ\text{C}$ , the heat flux generated by the internal source is bi-directional. A portion of the energy is directed towards the building interior, effectively acting as a radiant heater, while the remainder is dissipated through the external pane. A fundamental finding of this analysis is the concept of the zero-loss threshold. By modulating the power supplied to the heating element, the internal surface temperature can be adjusted to match the indoor air temperature. At this specific set-point, the net heat flux from the room to the window is nullified, effectively eliminating the window’s role as a thermal bridge. This state of thermal equilibrium suggests that active glazing can function as a “thermally neutral” barrier, which is a significant departure from the performance of conventional passive TGUs.

### 3.2. Surface temperature distribution and external heat loss

The thermal profiles of the glazing surfaces, recorded using Pico Type K thermocouples, are illustrated in Figure 4. The experimental results demonstrate that while the integrated heating system effectively mitigates the “cold pane” effect, thereby enhancing indoor thermal comfort, it also induces a higher external surface temperature, which subsequently increases radiative and convective heat losses to the environment.

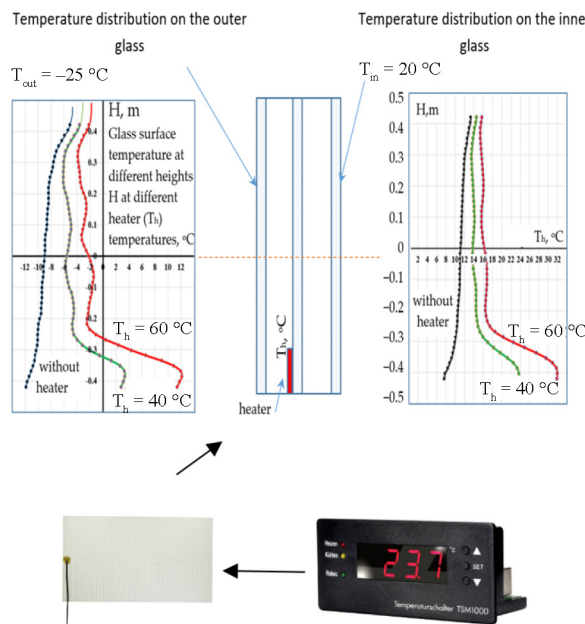


Figure 4. Thermal profiles of the window surfaces under active heating conditions

Analysis of the experimental results at an outdoor temperature of  $0 \text{ }^\circ\text{C}$  reveals that the heat flux generated by the heater is partitioned, being directed both into the

interior space and towards the external environment. It is evident that by precisely modulating the heater's output to a specific lower threshold, a zero-net thermal balance can be achieved for the window. Reaching this equilibrium effectively nullifies heat transfer through the glazing, thereby eliminating conventional transmission losses.

However, it must be noted that under all investigated heating scenarios, the external pane of the active window exhibits a higher heat loss magnitude compared to the reference (non-heated) window. This phenomenon is a direct consequence of the increased temperature gradient ( $\Delta T$ ) between the heated glass surface and the outdoor environment. Specifically, the data from Figure 3 confirms that as the heater power increases, the heat flux towards the outside also escalates. This increased external dissipation must be accounted for in the overall energy balance of the building. Consequently, a net positive energy effect for the indoor environment is best achieved when such active systems are coupled with supplementary energy sources or thermal storage technologies, as demonstrated in prior studies (Wang et al., 2024; Zhou et al., 2022).

It is important to acknowledge the practical limitations of the current active system. While the integrated heating effectively maintains thermal neutrality under controlled wind conditions in the chamber, the system's performance may vary under rapid, fluctuating outdoor gusts due to thermal inertia. Furthermore, the present experimental phase focused solely on thermal and convective heat transfer. The complex impact of solar radiation, which introduces additional solar heat gain, was excluded to isolate the heating element's efficiency. These factors will be further investigated in future studies.

### 3.3. Effects and future integration

The observed increase in external heat loss poses a challenge for net energy efficiency. However, this study demonstrates that the "positive thermal effect" (the reduction of indoor heating demand) can outweigh the increased external dissipation if managed correctly. To optimize this balance, the integration of supplementary energy sources is essential.

The experimental findings support the proposition that active windows should be coupled with renewable energy technologies, such as semi-transparent photovoltaics. This integrated approach facilitates a self-sustaining operational model, allowing the window to power its heating requirements during peak cold periods. Consequently, a "near-zero thermal loss" state can be maintained without increasing the building's total grid-energy consumption, transforming the glazing from a passive component into an active, energy-generating device within the sustainable building envelope.

A comprehensive evaluation of the glazing's total thermal balance necessitates the consideration of additional environmental variables, most significantly solar

irradiance. However, as the climatic chamber utilized in this study lacks a solar simulator, the direct impact of solar heat gains was excluded from this laboratory phase. To address this limitation, subsequent research will involve in-situ "natural experiments" under real meteorological conditions. This field-testing phase will facilitate a precise assessment of the system's efficiency, accounting for the dynamic influence of diurnal solar radiation and the absence of such gains during nocturnal periods. Furthermore, the proposed integration of photovoltaic panels will be managed by a demand-responsive control logic. Governed by high-precision sensors situated within the glazing cavity, the system will be calibrated to activate the heating element exclusively when the temperature within the inter-pane gap falls below a predefined thermal threshold. This ensures that active thermal compensation occurs only when transmission losses are detected, thereby optimizing the overall energy performance and autonomy of the building envelope component.

## 4. Conclusions

The experimental investigations presented in this study provide a comprehensive evaluation of the thermal performance and operational characteristics of an active glazing system equipped with integrated electrical heating. By employing a high-precision instrumentation suite, comprising Hukseflux FHF05 thin-film flexible heat flux sensors coupled with an LI19 data logger, alongside Pico Type K thermocouples monitored via a four-channel digital thermometer (TM-947SD, Lutron). Based on the experimental results and the subsequent analysis, the following primary conclusions can be established:

1. The results confirm that precise modulation of the heating element allows for a "near-zero thermal balance." At an external temperature of 0 °C, adjusting the heater to a specific threshold nullifies the net heat flux from the interior to the window. This effectively transforms the glazing from a conventional thermal bridge into a thermally neutral barrier, eliminating standard transmission losses.
2. The active system significantly enhances indoor thermal comfort. As shown in the thermal profiles (Figure 4), at an extreme outdoor temperature of -25 °C, the internal glass surface temperature without heating drops to approximately +12 °C. Activation of the heater ( $T_h = 60$  °C) elevates this surface temperature to approximately +16 °C to +18 °C, effectively eliminating the radiant "cold pane" effect and the risk of surface condensation.
3. Quantitative analysis (Figure 3) reveals that internal heating induces a bi-directional heat flow. While it improves indoor comfort, it also increases the temperature of the outer pane (from -8 °C to -2 °C at  $T_{out} = -25$  °C), which escalates external heat dissipation. At the highest heating power ( $T_h = 60$  °C), the outward

heat flux reaches values  $180 \text{ W/m}^2$ , compared to approximately  $60 \text{ W/m}^2$  for the standard unit without heating.

4. To maximise net energy efficiency and long-term sustainability, the findings support the integration of active windows with renewable energy harvesting technologies. Coupling these units with semi-transparent photovoltaics would allow the window to function as an active, self-powering element of the building envelope. Such integration is essential to further reducing reliance on the power grid and achieving NZEB standards.

5. While the system demonstrated robust thermal stability under laboratory-simulated controlled temperature gradients, its operational performance under transient environmental fluctuations, such as high-velocity wind gusts or abrupt shifts in ambient temperature, warrants further investigation. The present experimental phase focused on steady-state regimes to isolate the specific thermal efficiency of the integrated heating element. However, subsequent research will transition to in-situ “natural experiments” to evaluate the complex impact of diurnal solar radiation, which was excluded from this phase due to the technical limitations of the climatic chamber regarding solar simulation. These future field trials will be critical for optimizing the dynamic interaction between the active heating system, the integrated photovoltaic system, and varying meteorological stressors, thereby ensuring the systems resilience and efficiency in real-world architectural applications.

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