

Influence of Power Distribution on Surface Temperature Homogeneity in Aluminium Hot-Plate Heaters for PVC Window Welding

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(Geliş/Received: 13/01/2026;

Kabul/Accepted: 11/03/2026)

Abstract: The surface temperature uniformity of aluminium hot-plate heaters is a key factor affecting weld quality in PVC hot-plate welding. Although aluminium plates are widely preferred for their high thermal conductivity, the effect of internal power distribution on surface temperature homogeneity under constant total power has not been thoroughly quantified. This study investigates the transient thermal behaviour of an aluminium heating plate using a three-dimensional numerical heat conduction model including internal heat generation and convection–radiation losses. Two power-distribution scenarios—symmetric (1250–1250 W) and asymmetric (1000–1500 W)—were examined with a fixed total power of 2500 W. Both reached the target temperature of 240 °C in similar times (~321 s), showing that overall heating behaviour is dictated mainly by total input power. However, spatial temperature differences were significant. The symmetric case produced global surface variations of ~30 °C, whereas the asymmetric case reduced this range to ~18 °C. In the active welding zone, temperature variation decreased from ~15 °C (symmetric) to only 4–5 °C (asymmetric). These results demonstrate that heat-flux balance, rather than electrical symmetry, governs temperature uniformity. Therefore, internal power distribution represents an independent thermal design parameter and provides a practical basis for optimizing aluminium hot-plate heaters used in industrial PVC welding systems.

Keywords: Numerical analysis, heating element, PVC hot-plate welding, power distribution, temperature homogeneity.

PVC Pencere Kaynağı için Alüminyum Sıcak-Plaka Isıtıcılarda Güç Dağılımının Yüzey Sıcaklığı Homojenliğine Etkisi

Öz: Alüminyum sıcak-plaka ısıtıcıların yüzey sıcaklığı homojenliği, PVC sıcak-plaka kaynağında kaynak kalitesini doğrudan etkileyen temel bir parametredir. Alüminyum plakalar yüksek ısı iletkenlikleri nedeniyle yaygın olarak kullanılmasına rağmen, sabit toplam güç altında iç güç dağılımının yüzey sıcaklık homojenliğine etkisi yeterince nicel olarak incelenmemiştir. Bu çalışmada, iç ısı üretimi ve konveksiyon-radyasyon kayıplarını içeren üç boyutlu zamana bağlı bir ısı iletimi modeli kullanılarak bir alüminyum sıcak-plaka ısıtıcısının termal davranışı analiz edilmiştir. Toplam güç 2500 W sabit tutulmak üzere iki senaryo—simetrik (1250–1250 W) ve asimetrik (1000–1500 W) incelenmiştir. Her iki durumda da hedef sıcaklık olan 240 °C'ye benzer sürelerde (~321 s) ulaşılmış, böylece küresel ısınma davranışının esas olarak toplam güç girdisi tarafından belirlendiği doğrulanmıştır. Ancak uzamsal sıcaklık dağılımları belirgin şekilde farklıdır. Simetrik dağılım ~30 °C'lik bir yüzey sıcaklık aralığı oluştururken, asimetrik dağılım bu aralığı ~18 °C'ye düşürmüştür. Aktif kaynak bölgesinde sıcaklık değişimi simetrik durumda ~15 °C iken, asimetrik durumda 4–5 °C seviyesine inmiştir. Sonuçlar, sıcaklık homojenliğinin elektriksel simetriden ziyade ısı akısı dengesine bağlı olduğunu göstermekte ve güç dağılımının bağımsız bir termal tasarım parametresi olduğunu ortaya koymaktadır.

Anahtar kelimeler: Sayısal analiz, ısıtma elemanı, PVC ısıtma plakası kaynağı, güç dağıtımı, sıcaklık homojenliği.

1. Introduction

Hot plate welding is one of the most widely employed joining techniques in the industrial manufacturing of polyvinyl chloride (PVC) window profiles owing to its high repeatability, mechanical reliability, and suitability for mass production. In this process, the mating surfaces of the thermoplastic profiles were heated in a controlled manner by contact with a heated metallic plate (Figure 1a). Heating was continued until a defined softening state was reached, after which the profiles were consolidated under pressure to form a durable welded joint (Figure 1b). Beyond the cycle time and setpoint temperature, the surface temperature homogeneity of the heating plate directly governs the melt depth, interdiffusion, and stress development, making it a first-order variable for weld strength.

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Although hot plate welding is primarily assessed from a process-performance perspective, the broader sustainability of PVC-based products has also attracted significant scientific attention. Leadbitter [1] evaluated PVC within a science-based sustainability framework and demonstrated that when assessed over its full life cycle, PVC can be considered a sustainable material, provided that the manufacturing processes are optimized to preserve material integrity and minimize energy and resource inefficiencies. In this regard, joining processes such as hot-plate welding play a decisive role, as thermal nonuniformities and process-induced defects may compromise both the mechanical performance and long-term sustainability of PVC window profile systems.

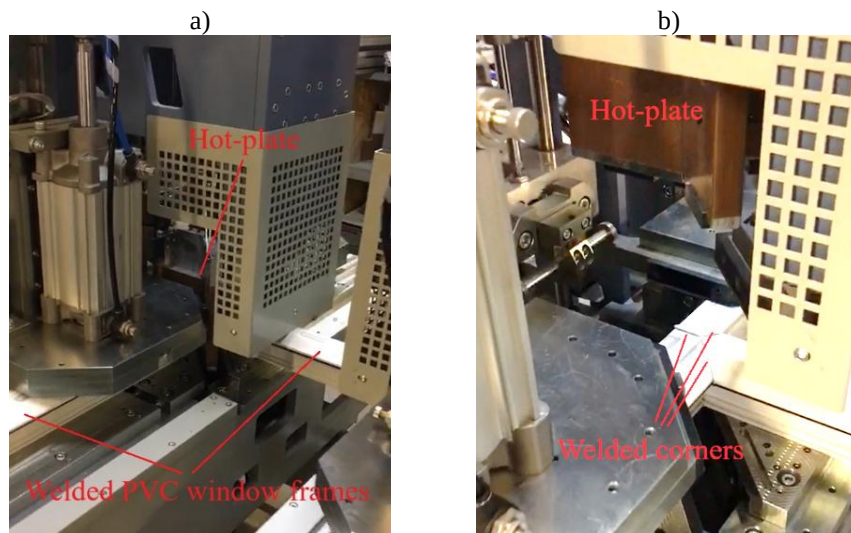


Figure 1. Hot-Plate Heaters for PVC Welding: a) Welded PVC frames during welding process, b) Welded corners after welding process.

Industrial standards and technical guidelines, such as those issued by the European PVC Window Profile and Related Building Products Association (EPPA), define an optimal operating temperature window of approximately 235–255 °C for PVC hot-plate welding [2]. While maintaining the mean surface temperature within this window is essential, numerous studies have shown that local temperature gradients across the heating plate are equally important. Non-uniform surface temperatures can directly affect the melt depth, molecular interdiffusion, and stress development within the joint, leading to heterogeneous plasticization, residual stress accumulation, and premature failure at the welded corners. Consequently, surface temperature homogeneity has emerged as a key quality indicator in addition to traditional process parameters.

From a thermal engineering perspective, the temperature field of a hot-plate heater is governed by the interaction between internal heat generation, material thermal conductivity, and external heat losses, primarily via natural convection and, to a lesser extent, thermal radiation. Several analytical and numerical studies have been conducted to characterize the heat transfer behavior of hot-plate welding systems. Wałęsa [3] investigated both temporal and spatial temperature variations during hot-plate welding and demonstrated that accurate thermal modelling is essential for predicting process-specific parameters, such as plasticization depth. Their work highlighted that even small modelling inaccuracies in the temperature field can lead to significant deviations in weld-quality predictions.

In addition to conventional hot-plate systems, resistive-heating-based welding approaches have been extensively investigated for thermoplastic composites. Stavrov and Bersee [4] examined the influence of heater geometry, power density, and heat source placement on the thermomechanical behaviour of resistance-welded joints and showed that the heater design directly affects the energy efficiency, stress accumulation, and joint integrity. Recent CFD-based studies have confirmed these results. Özkaymak [5] demonstrated that heterogeneous heat distribution in thermoplastic composite manufacturing leads to mechanical weaknesses, whereas Zaidan and Alhamdo [6] experimentally quantified the influence of different heater configurations on surface temperature homogeneity.

Experimental comparisons of thermal welding techniques further support the importance of a controlled power input. Marcellić et al. [7] compared the temperature profiles in hot-wedge and hot-air welding methods and showed that improper power adjustment can significantly degrade thermal uniformity. In high-temperature applications, Giuliatti et al. [8] emphasized that a CFD-based assessment of temperature uniformity is critical for accurately characterizing the thermal performance and associated emissions. Collectively, these studies emphasize that thermal stability and uniform heat distribution are fundamental prerequisites for achieving mechanically robust welded joints.

Recent studies have increasingly focused on data-driven modelling of hot-plate welding processes. For example, Novakovic and Kashkoush [9] employed regression and support vector machine models to describe the material displacement during the matching stage of HDPE hot-plate welding. However, these approaches primarily address process parameter adjustments and do not explicitly resolve the thermal field or surface temperature homogeneity of heating plates.

However, despite these advances, an important limitation remains unaddressed. Industrial hot-plate welding machines commonly employ aluminium heating plates with multiple resistive elements arranged in geometrically symmetric layouts. Aluminium is favoured because of its high thermal conductivity and rapid heat-spreading capability, which mitigates extreme temperature gradients. However, high conductivity alone does not guarantee an isothermal surface when internal heat generation is spatially unbalanced. In practice, resistive elements are frequently supplied with non-uniform electrical power owing to design constraints or control strategies. Under these conditions, an asymmetric power input can still induce a pronounced thermal asymmetry at the welding interface, even when the heater geometry is perfectly symmetric.

Experimental investigations on PVC window-frame welding have demonstrated that inadequate temperature control is one of the primary causes of quality degradation at welded corners. Wygoda et al. [10] reported significant discrepancies between the set welding temperature and actual contact temperature, which directly affected the flexural strength of the PVC corner joints. Their results, obtained from bending tests and digital image correlation, indicated that thermal inconsistencies during welding can lead to premature failure and a reduction in joint durability. Among the existing modelling efforts, Wałęsa et al. [11] provided an experimental–analytical description of the plasticizing stage in hot-plate welding, emphasizing the importance of accurate thermal conditions for predicting material flow behaviour. However, the thermal response of heating plates under asymmetric internal power generation has not been fully investigated.

Although recent studies have shown that direct resistive heating offers rapid heating rates and, with appropriate design, acceptable temperature uniformity [12], systematic investigations that isolate the effect of power distribution under a constant total input power remain limited. In particular, quantitative comparisons of symmetric and asymmetric power supply scenarios using identical heater geometries remain limited, particularly for aluminium hot-plate heaters used in PVC welding applications.

To address this gap, this study conducted a systematic three-dimensional transient numerical heat transfer analysis of an aluminium hot-plate heater used in PVC corner welding. Two power-distribution scenarios were investigated while maintaining a constant total power input of 2500 W: an asymmetric (1000–1500 W) and a homogeneous configuration (1250–1250 W). The effect of the resistance power distribution on the surface temperature homogeneity was isolated by keeping the heater geometry, material properties, and boundary conditions constant. The primary objective of this study was to quantify the effect of power distribution on transient heating behaviour and surface temperature homogeneity within the EPPA-recommended welding temperature range. The results demonstrate that balanced power distribution constitutes a critical and independent thermal design parameter that is comparable in importance to heater geometry and total power level, and provides practical guidance for optimizing hot-plate welding systems in the industrial manufacture of PVC window profiles, including recommendations for future experimental validation of the proposed model.

2. Theoretical Framework

Accurate modelling of the thermal behaviour of aluminium heating plates used in PVC hot-plate welding requires a physically consistent representation of transient energy storage, internal heat conduction and external heat losses. In this study, a three-dimensional transient heat conduction model with internal heat generation was developed to describe the thermal response of the heating plate. Heat dissipation from external surfaces was accounted for using convection and thermal radiation boundary conditions.

Since no internal fluid motion exists within the aluminium block, the problem reduces to transient heat conduction in a solid domain. The surrounding air was not explicitly resolved using the Navier–Stokes equations; instead, its thermal effect was represented using appropriate surface heat transfer coefficients. Therefore, the model

represents a transient solid heat conduction formulation with external convection–radiation boundary conditions, rather than a fully resolved conjugate heat transfer simulation.

The thermophysical properties of aluminium (density, specific heat capacity, and thermal conductivity) were assumed to be constant over the investigated temperature range. This assumption is justified by the relatively moderate temperature variations encountered during the welding cycle and is consistent with the common practice in industrial heating simulations.

2.1 Governing energy equation and solid-state heat conduction

Heat transfer within the aluminium plate is governed by the transient heat conduction equation with internal heat generation, as expressed in Equation (1):

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q''' \quad (1)$$

where ρ is the density, k is the thermal conductivity, c_p is the specific heat capacity, and q''' is the volumetric heat generation rate (W/m^3). Equation (1) follows directly from the general conservation of energy for a stationary solid with internal heat generation. Owing to the high thermal conductivity of aluminium ($k \approx 200\text{--}240 \text{ W/m}\cdot\text{K}$ in the considered temperature range), lateral heat diffusion occurs rapidly, significantly reducing internal temperature gradients and promoting surface temperature homogenization [13]. Although natural convection occurs in the surrounding air, this study primarily focused on the thermal response of a solid heating plate. Therefore, a detailed modelling of airflow structures was not pursued, and the air domain was treated using appropriate thermal boundary conditions.

2.2. Modelling of resistive heat generation

The thermal input from each resistance heater was applied as a uniform heat flux boundary condition on the inner surfaces of the corresponding heater cavities within the aluminium plate. The total thermal power transferred from each heater surface integral of the local heat flux, as stated in Equation (2) [13]:

$$\dot{Q}_{gen} = \int_A q'' dA \quad (2)$$

where q'' is the surface heat flux and A is the effective inner surface area of the heater cavity. Assuming a uniform heat flux distribution over each heater surface, Equation (2) simplifies to the heat-flux expression given in Equation (3):

$$q'' = \frac{P_i}{A_i} \quad (3)$$

where P_i is the electrical power assigned to the i^{th} resistance heater and A_i is the corresponding inner surface area (m^2). In both configurations, the total electrical input power was maintained at 2500 W.

The thermal contact resistance between the heaters and the aluminium block was neglected, assuming perfect thermal bonding and ideal conductive heat transfer at the interfaces. This assumption is appropriate for the tightly fitted cartridge-type heaters commonly used in industrial heating plates.

Two power distribution scenarios were analysed:

- Asymmetric power distribution: 1000 W – 1500 W
- Symmetric power distribution: 1250 W – 1250 W

In both cases, the total electrical input power was maintained at 2500 W. By preserving the identical geometry, material properties, and boundary conditions, the symmetry of the power distribution was isolated as the sole independent variable, enabling a clear assessment of its influence on the surface temperature uniformity [13].

2.3. Boundary conditions: natural convection and heat losses

All external surfaces of the heating plate were exposed to ambient air, resulting in heat loss through natural convection and thermal radiation. The convective heat transfer at the solid–air interface was modelled using Newton’s law of cooling as expressed in Equation (4):

$$q''_{conv} = h(T_s - T_\infty) \quad (4)$$

where h is the natural convection heat-transfer coefficient, T_s is the surface temperature, and T_∞ is the ambient temperature. For horizontal heated plates under free convection, typical values of h range between 2–10 W/m²·K depending on the Rayleigh number and temperature difference [14]. Based on characteristic length and operating temperature differences in the present configuration, a representative constant value of $h=5$ W/m²·K was adopted as an engineering approximation.

Thermal radiation heat loss was incorporated using the Stefan–Boltzmann relation shown in Equation (5):

$$q''_{rad} = \varepsilon\sigma(T_s^4 - T_\infty^4) \quad (5)$$

where ε is the surface emissivity of aluminium, and $\sigma=5.67\times10^{-8}$ W/m²·K⁴ is the Stefan–Boltzmann constant. The total heat loss from a surface is therefore obtained by multiplying the above heat flux expressions by the corresponding exposed surface area.

2.4. Transient heating model and heating time estimation

The transient thermal response of the heating plate can be analytically approximated using a global energy balance. Under idealized adiabatic conditions (i.e., neglecting heat losses), the time required to increase the plate temperature from the initial temperature T_0 to the target welding temperature T_{target} can be estimated using a lumped-capacitance formulation given in Equation (6):

$$t_{ideal} = \frac{mc_p(T_{target} - T_0)}{P_{total}} \quad (6)$$

where m denotes the plate mass and P_{total} denotes the total electrical power input. Equation (6) assumes spatially uniform temperature within the solid, which corresponds to the lumped-capacitance approximation. The validity of this assumption was assessed using the Biot number, defined in Equation (7):

$$Bi = \frac{hL_c}{k} \quad (7)$$

where h represents the convective heat transfer coefficient, L_c is the characteristic length obtained from the ratio of volume to surface area, and k denotes the thermal conductivity of aluminium. Owing to the high thermal conductivity of aluminium and moderate convection coefficients, the Biot number remained well below 0.01 under all operating conditions. This confirms that the internal temperature gradients are negligible compared to the surface temperature differences, validating the lumped-capacitance approximation for the analytical heating time estimation. However, as the plate temperature increases, convective and radiative heat losses reduce the net heating power available for the temperature increase. Incorporating these losses leads to a temperature-dependent energy balance expressed in Equation (8):

$$mc_p \frac{dT}{dt} = P_{total} - hA(T - T_\infty) - \varepsilon\sigma A(T^4 - T_\infty^4) \quad (8)$$

Integrating Equation (8) between T_0 and T_{target} yields the realistic heating time, as given in Equation (9):

$$t_{real} = \int_{T_0}^{T_{target}} \frac{mc_p}{P_{total} - hA(T - T_\infty) - \varepsilon\sigma A(T^4 - T_\infty^4)} dT \quad (9)$$

Equation (9) shows that the heating time increases nonlinearly with temperature, primarily because of the fourth-power dependence of radiative heat losses. This formulation provides a theoretical basis for interpreting transient numerical simulations and quantifying the deviation between ideal and realistic heating performances.

2.5. Modelling assumptions

To ensure numerical robustness while maintaining computational efficiency, the following assumptions were adopted:

- The constant thermophysical properties of aluminium were employed ($\rho = 2702 \text{ kg/m}^3$, $c_p = 903 \text{ J/kg}\cdot\text{K}$, $k = 237 \text{ W/m}\cdot\text{K}$). This assumption is justified by the relatively narrow operating temperature range ($\sim 20\text{--}255 \text{ }^\circ\text{C}$) over which the variation in these properties is small.
- Resistance heaters were modelled as void cavities within the aluminium plate, with a uniform heat flux boundary condition applied to the inner surfaces of each cavity.
- Contact between the heating plate and the PVC profiles was excluded from the model.
- Steel support plates were omitted because their high thermal conductivity did not introduce a significant additional thermal resistance.

These assumptions allow for a focused and reliable assessment of surface temperature homogeneity, which constitutes the primary performance metric examined in this study.

In reality, the natural convection coefficient depends on the Rayleigh number and surface temperature; however, because the present study focuses on a comparative assessment under identical boundary conditions, adopting a constant value ensures methodological consistency.

3. Numerical Analysis

The transient thermal problem was solved using an implicit unsteady formulation to ensure numerical stability during extended heating periods and in the presence of steep temperature gradients [15]. The heat conduction within the solid aluminium domain was solved using an implicit transient solid heat conduction formulation. This approach significantly reduces the computational cost while maintaining the accuracy required for surface temperature prediction.

The spatial discretization of the conduction term employed a second-order accurate scheme, whereas the temporal discretization employed a second-order implicit time integration method. This combination minimizes numerical diffusion and ensures an accurate resolution of the transient thermal behaviour.

The simulations were conducted using a fixed time step of 0.1 s, providing a suitable balance between temporal resolution and computational efficiency. Solution convergence was ensured by imposing a residual convergence criterion of 10^{-5} for all governing equations. Instead of prescribing a fixed simulation time, each transient run continued until the surface-averaged temperature of the heating plate reached the target welding temperature of $240 \text{ }^\circ\text{C}$. This physically based termination criterion ensures that the thermal response is evaluated under conditions that are directly relevant to the welding process. At this stage, the temporal variations in the surface-averaged temperature became negligible, indicating that the system had reached a quasi-steady thermal regime.

3.1. Geometry and modelling strategy

The three-dimensional geometry of the aluminium heating plate employed in the PVC hot-plate welding process is shown in Figure 2. The heater was manufactured from aluminium with a thermal conductivity of $237 \text{ W/m}\cdot\text{K}$, enabling rapid lateral heat spreading and promoting thermal uniformity under balanced heating conditions. The PVC profiles contacted the heating plate at the two flat welding surfaces located on the outer faces of each arm of the welding mirror. These contact surfaces correspond to the elliptically marked active welding zones shown in Figure 6.

The heating plate incorporates two independent resistance circuits, designated as Resistance 1 and Resistance 2, which are embedded symmetrically within each arm of the welding mirror. Resistance 1 had an effective heating surface area of 0.01258 m^2 , whereas Resistance 2 had an effective heating surface area of 0.01925 m^2 . Although the geometric layout of the resistive elements was symmetric, a thermal asymmetry was intentionally introduced by prescribing unequal electrical power inputs to the two heaters.

Two power input configurations were investigated:

Asymmetric power distribution:

Resistance 1 = 1000 W (heat flux $\approx 79.5 \text{ kW/m}^2$)

Resistance 2 = 1500 W (heat flux ≈ 77.9 kW/m²).

This intentional power imbalance was introduced to equalize the heat flux density across both resistance zones, thereby compensating for their unequal effective surface areas.

Symmetric power distribution:

Resistance 1 = 1250 W (heat flux ≈ 99.3 kW/m²)

Resistance 2 = 1250 W (heat flux ≈ 64.9 kW/m²).

In this configuration, identical electrical power inputs resulted in significantly different heat flux densities owing to the unequal heater surface areas.

The supporting steel plates were excluded from the numerical models. The thermocouple ports and bolt holes were explicitly modelled as void regions to capture local geometric discontinuities and their influence on the heat transfer behaviour.

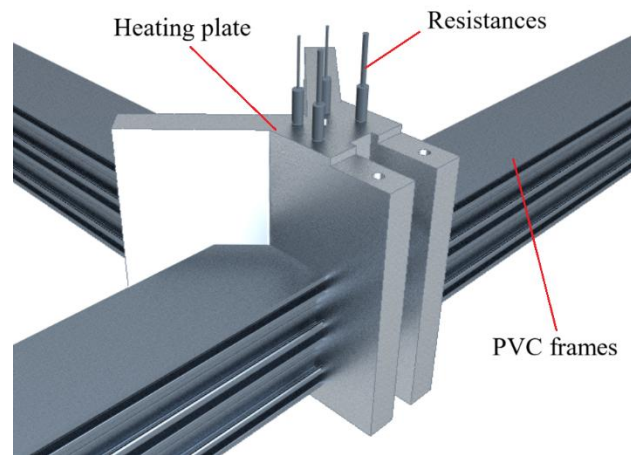


Figure 2. Three-dimensional geometry of the aluminium heating plate with resistance layout and PVC frame contact regions in the hot-plate welding process.

3.2. Thermal homogeneity assessment

In PVC hot-plate welding, surface temperature homogeneity is a critical performance indicator because it directly governs the melt depth, molecular interdiffusion, and joint integrity. Accordingly, the influence of symmetric (1250–1250 W) and asymmetric (1000–1500 W) power distribution scenarios on the surface temperature field was quantitatively assessed. The active welding region, defined as the contact zone between the heating plate surface and PVC profiles (indicated by the elliptical markers in Figure 6), was selected as the primary evaluation area because it directly governs the weld quality.

3.3. Initial and boundary conditions

The computational domain and the applied boundary conditions are shown in Figure 3. The heating plate was initially set to a uniform temperature of 20 °C, and the ambient air was maintained at 20 °C. Natural convection heat losses were modelled by applying a convective boundary condition to all exposed surfaces [16] with a heat transfer coefficient $h = 5$ W/m²·K (see Section 2.3). Adiabatic boundary conditions were imposed on the thermocouples and bolt connections.

The thermophysical properties of aluminium used in the simulations are listed in Table 2. Constant property values were adopted throughout the study, consistent with the modelling assumptions stated in Section 2.5.

Table 2. Thermophysical properties of aluminium used in the numerical simulations.

Property	Symbol	Value	Unit
Density	ρ	2702	kg/m ³

Specific heat capacity	c_p	903	J/kg·K
Thermal conductivity	k	237	W/m·K

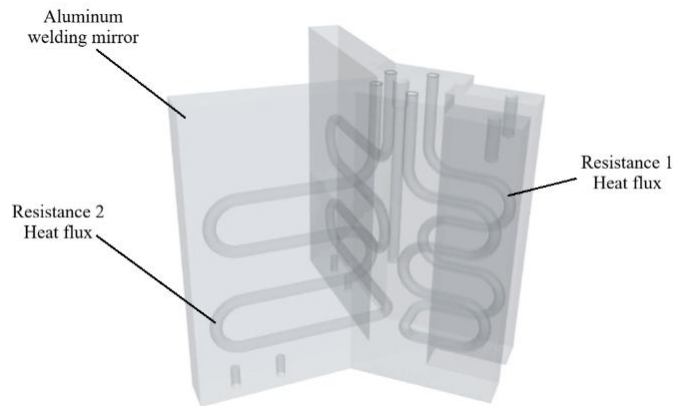


Figure 3. Computational domain and applied boundary conditions.

3.4. Numerical mesh and grid independence

Polyhedral meshes offer improved numerical stability and accuracy compared with tetrahedral meshes for an equivalent cell count, making them particularly suitable for numerical heat transfer analyses involving complex solid geometries. To ensure thermal continuity at the resistance–aluminium interface, where heat transfer is most pronounced, a conformal meshing strategy with a shared topology was employed during the CAD preparation stage. This approach guarantees node matching at all solid–solid interfaces, ensuring the continuity of the heat flux without interpolation errors. Because heat transfer occurs from the inner cavity surface directly into the surrounding aluminium domain, a conventional inflation layer was neither applicable nor required at this location. Figure 4 presents a cross-sectional view of the mesh at this interface, illustrating the local refinement in this thermally critical zone.

The mesh quality was assessed using four standard metrics. The maximum skewness angle was 78.4°, remaining below the acceptable threshold of 85°. The face validity was 1.0 for all cells, confirming the absence of degenerate or inverted faces. The volume ratio remained above 1.1×10^{-2} , well within the acceptable range, and the aspect ratio and non-orthogonality values were within the limits that are commonly recommended for polyhedral meshes in conduction-dominated numerical simulations. Collectively, these metrics confirm that the mesh quality is sufficient for an accurate and stable transient thermal analysis.

A grid independence study was conducted using three mesh configurations with approximately 400,000, 520,000, and 650,000 cells. The variation in the average surface temperature between the 520,000-cell and 650,000-cell meshes was below 1%. Accordingly, the ~520,000-cell configuration was selected as the optimal balance between the computational efficiency and solution accuracy.

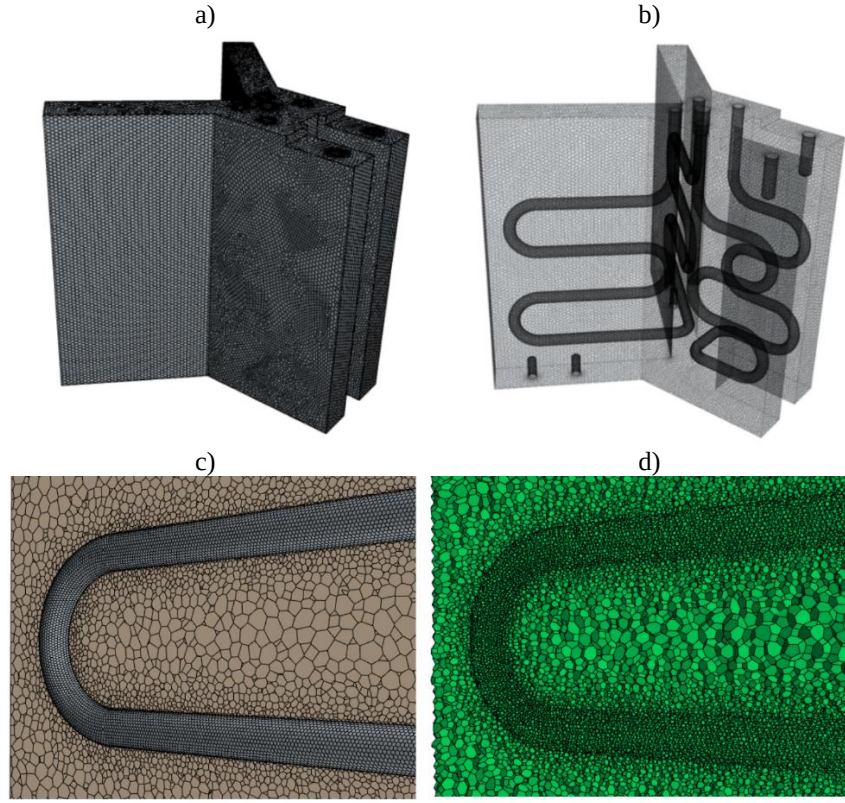


Figure 4. Polyhedral computational mesh: (a) external surface discretisation of the aluminium plate, (b) transparent cross-sectional view showing the internal resistance channel layout, (c) detailed polyhedral cell structure at the resistance–aluminium interface, and (d) close-up view of the conformal mesh at the resistance channel cross-section.

4. Results and Discussion

4.1. Surface temperature distribution and transient thermal response

The transient thermal behaviour of the aluminium heating plate was analysed under two resistance power distribution scenarios: asymmetric (AD: 1000–1500 W) and symmetric (SD: 1250–1250 W). Figure 5 shows the temporal evolution of the average surface temperature for both scenarios. In both cases, the surface temperature increased almost linearly with time during the heating phase, indicating a stable and predictable thermal response without any abrupt transients.

Despite the distinct spatial power distributions, both configurations reached a target welding temperature of 240 °C after approximately 321 s. This behaviour is consistent with the global energy balance governed by the first law of thermodynamics, confirming that the heating time is primarily controlled by the net power input rather than the spatial power allocation. The observed near-linear temperature increase reflects the high thermal conductivity of aluminium, which facilitates rapid internal heat redistribution and limits the development of significant internal temperature gradients. Consequently, the heating plate behaves as a thermally compact system during the transient heating phase, particularly before surface heat losses become dominant in the energy balance.

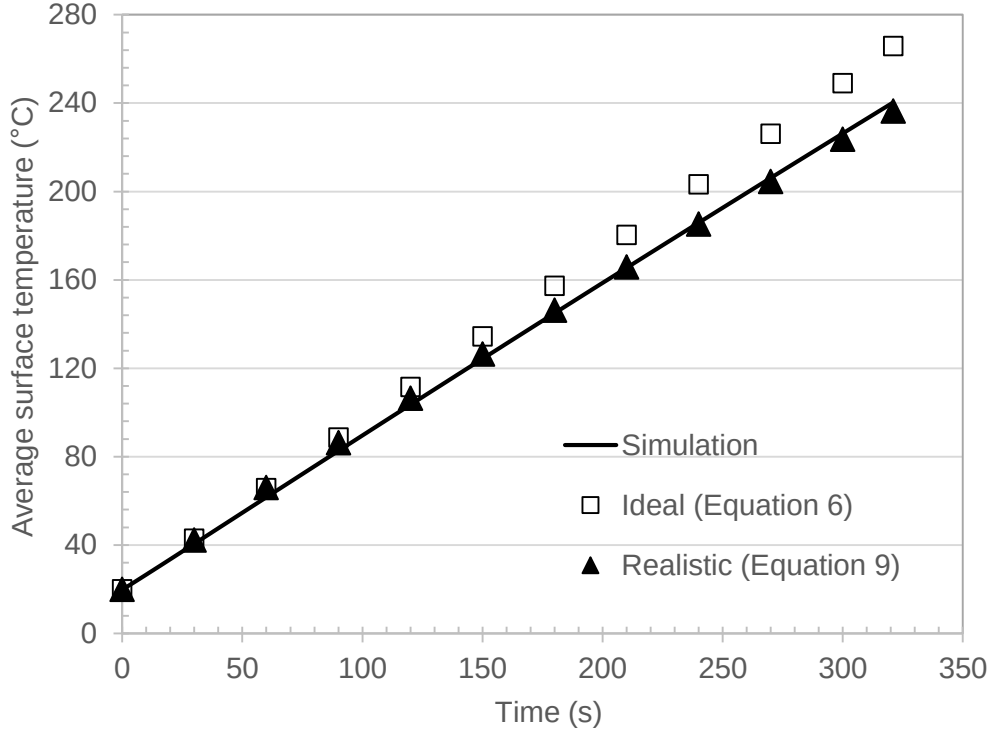


Figure 5. Temporal evolution of average surface temperature compared with theoretical heating limits.

4.2. Comparison with theoretical heating predictions and model validation

The numerically predicted heating time of 321 s closely matched the analytically derived ideal heating time obtained from the lumped energy balance presented in Equation (6). Using the known mass of the aluminium plate, constant specific heat ($c_p = 903 \text{ J/kg}\cdot\text{K}$), temperature increase from 20°C to 240°C , and total electrical power input of 2500 W, the theoretical heating time was calculated and found to be in strong agreement with the numerical result.

The small deviation between the numerical and analytical predictions can be attributed primarily to convective and radiative heat losses incorporated in the numerical model but neglected in the ideal lumped-capacitance estimate, as well as minor numerical discretization effects. This agreement verifies the global energy conservation and thermodynamic consistency of the numerical implementation.

Importantly, this comparison confirms that the spatial temperature differences analysed in subsequent sections are not artifacts of incorrect global energy accounting. Rather, they originate from the imposed differences in the internal power distribution under otherwise identical boundary and material conditions. Although experimental validation is planned for future work, the present analytical comparison provides a physically grounded verification of the model. Furthermore, the loss-inclusive analytical formulation (Eq. 9) confirms that the heat losses remain within a physically reasonable range and do not alter the comparative conclusions regarding the surface temperature homogeneity.

4.3. Surface temperature homogeneity and implications for weld quality

Although the global heating behaviour of the system was unaffected by the resistance power distribution, pronounced differences were observed in the spatial temperature fields across the heating plate surface. Figure 6 presents the surface temperature contours obtained under quasi-steady conditions for both power distribution scenarios using a consistent temperature colour scale for direct visual comparison. The region corresponding to the contact area between the heating plate and PVC profile is highlighted by an elliptical marker, which corresponds to the welding surface locations shown in Figure 2.

Under symmetric power input (1250–1250 W), the overall surface temperature distribution exhibited the widest range. Across the entire surface of the heating plate, the temperature varied between 225 and 254 °C, yielding a maximum temperature difference of approximately 30 °C. This indicates that despite the equal total power supplied to both resistance circuits, the geometric differences in the resistor placement and effective heating areas can still lead to noticeable global thermal non-uniformities.

In contrast, the asymmetric power distribution (1000–1500 W) yielded a narrower global temperature range, with surface temperatures varying between approximately 228 and 246 °C. This corresponded to a maximum temperature difference of approximately 18 °C across the plate surface. A more detailed examination of the active welding region — the elliptical contact zone where the PVC profile is located — reveals that the local temperature variations within this zone are significantly smaller than the global temperature differences for both configurations. In this critical contact zone, the surface temperature variation under the asymmetric power distribution was limited to 4–5 °C, indicating sufficiently uniform thermal conditions for consistent PVC plasticization and molecular interdiffusion. Under symmetric power input, local variations reached approximately 15 °C, which may have led to a heterogeneous weld quality. Table 1 summarizes the key temperature metrics for both the configurations.

Table 1. Comparison of Temperature Variations.

Configuration	Global Min (°C)	Global Max (°C)	Global ΔT (°C)	Welding Zone ΔT (°C)
Symmetric (1250–1250 W)	225	254	29	15
Asymmetric (1000–1500 W)	228	246	18	4–5

From a design perspective, electrical symmetry does not guarantee thermal symmetry. An equal power supply to geometrically unequal resistance zones leads to imbalanced heat flux densities, which manifest as pronounced surface temperature gradients. Therefore, heat flux balancing is a more physically meaningful design criterion than power symmetry alone. The numerical results demonstrated that the resistance power asymmetry plays a decisive role in controlling surface temperature gradients. Under asymmetric power input, the maximum temperature variation across the active welding surface was limited to approximately 4–5 °C, indicating a high degree of thermal uniformity. These conditions favour uniform melting and consistent molecular bonding along the PVC welding interface. In contrast, the symmetric power distribution produced pronounced thermal gradients with local surface temperature differences of approximately 15 °C. These imbalances promote heterogeneous viscous flow and uneven molecular diffusion, which can adversely affect the weld strength and long-term joint durability.

The superior performance of the asymmetric configuration results directly from balanced heat flux distribution. By setting the power ratio proportional to the ratio of the resistance surface areas, this study achieved a near-uniform heat flux ($\sim 78 \text{ kW/m}^2$) across both heating zones. In contrast, the symmetric power setting resulted in a significant flux imbalance ($\sim 99 \text{ kW/m}^2$ vs. $\sim 65 \text{ kW/m}^2$). This confirms that the thermal uniformity in complex geometries is governed by the energy flux balance, and not merely by the symmetry of the power magnitude.

To provide a more comprehensive understanding of the three-dimensional temperature field, Figure 7 shows the cross-sectional temperature distributions obtained through the heating plate for both power configurations. These cross-sections reveal that the temperature gradients observed at the plate surface are consistent with the internal thermal field and maintain a more uniform internal temperature distribution throughout the plate thickness, particularly in the vicinity of Resistance 2 (the higher-power element), confirming that the heat flux balancing strategy is effective not only at the surface but also throughout the plate volume.

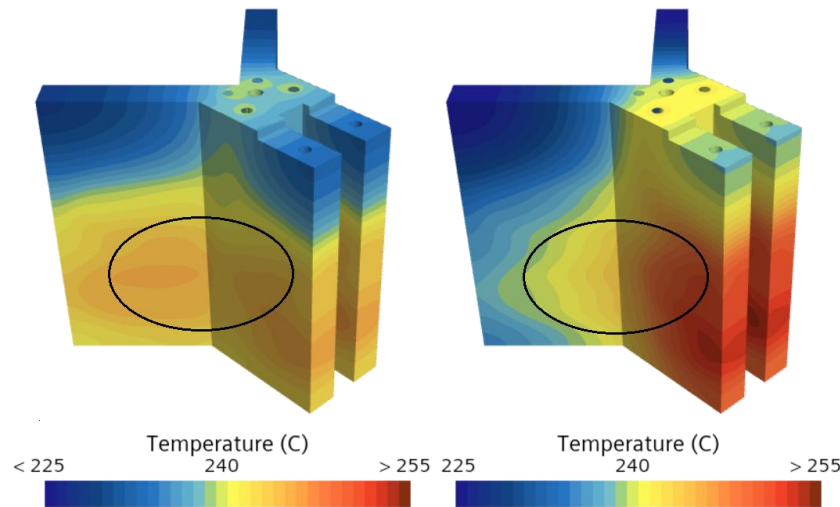


Figure 6. Effect of resistance power distribution on surface temperature contours (unified colour scale, 225–255 °C): a) symmetric (1250 W–1250 W) and b) asymmetric (1000 W–1500 W) configurations. Elliptical markers indicate the PVC-profile contact zone (active welding).

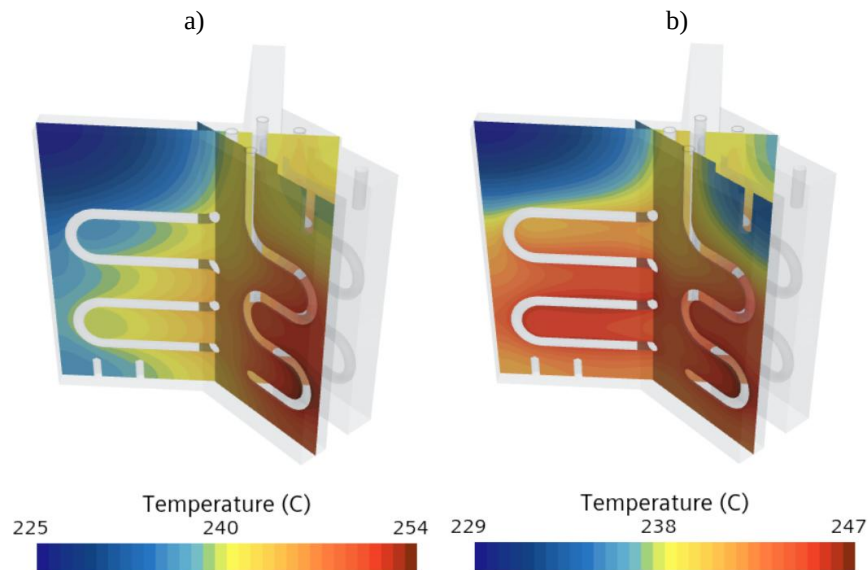


Figure 7. Cross-sectional temperature distributions through the heating plate: a) symmetric configuration (1250 W–1250 W); b) asymmetric configuration (1000 W–1500 W). The cross-sections reveal that the asymmetric power distribution maintains more uniform internal temperature gradients throughout the plate thickness, confirming the effectiveness of the heat flux balancing strategy.

These findings are consistent with the experimental observations reported in the literature, in which discrepancies between the set and actual welding temperatures affected the weld strength and durability of PVC corner joints [10]. The present results extend these observations by demonstrating that weld quality is governed primarily by the local thermal conditions at the contact interface rather than by the global temperature symmetry across the entire heating plate.

4.4. Design implications and optimisation outcome

The comparative analysis demonstrates that the tailored resistance-power asymmetry is a decisive, independent design parameter for achieving thermal uniformity in PVC hot-plate welding systems. Although both power configurations exhibited identical global heating times and energy consumption, the asymmetric power distribution substantially reduced the surface temperature gradients and suppressed local hotspot formation.

From an industrial perspective, these results indicate that improving the weld consistency and mechanical reliability does not necessarily require increased power levels or longer heating times. Instead, optimizing the distribution of resistance power based on a heat flux balance offers an effective energy-neutral pathway to enhance the thermal stability at the welding interface. Consequently, asymmetry in the resistance power should be considered along with the heater geometry and total power rating when designing and optimizing industrial hot-plate welding systems for PVC window profile manufacturing.

5. Conclusions

The three-dimensional transient heat conduction analysis demonstrates that, under a constant total power input of 2500 W, the distribution of resistance power decisively governs the surface temperature field of the aluminium heating plate. Although both the symmetric (1250 W–1250 W) and asymmetric (1000 W–1500 W) configurations exhibited nearly identical global heating behaviour, reaching the target welding temperature of 240 °C within comparable time frames (approximately 321 s), substantial differences emerged in the spatial temperature distribution.

The results indicate that a symmetric power distribution leads to larger global surface temperature variations, with maximum differences approaching 30 °C. In contrast, the asymmetric configuration produced a significantly narrower overall temperature range of approximately 18 °C. More critically, within the active welding region, where the PVC profiles contact the heating plate, the asymmetric configuration limited the temperature variation to approximately 4–5 °C, compared with approximately 15 °C in the symmetric case. This represents nearly a threefold improvement in local thermal uniformity and clearly demonstrates that global surface uniformity and local welding zone homogeneity do not necessarily coincide.

A fundamental insight emerging from this study is that electrical symmetry does not inherently guarantee thermal symmetry when the effective internal resistance surface areas are different. The analyses confirm that optimal thermal homogeneity is achieved only when the local heat flux density is balanced across the heating elements, rather than when identical electrical power values are supplied. In the present configuration, the asymmetric power allocation successfully compensated for the unequal resistive surface areas, resulting in an approximately uniform heat flux distribution ($\sim 78\text{--}80\text{ kW/m}^2$) across both heating zones. Therefore, from a design standpoint, heat flux balancing emerges as a more physically meaningful criterion than power symmetry alone.

Therefore, resistance power distribution should be treated as an independent and controllable thermal design parameter rather than assumed optimal under symmetric input. From an industrial perspective, these findings provide practical guidance for optimizing PVC hot-plate welding systems, demonstrating that appropriate tuning of the resistance power levels based on the heat-flux equilibrium can significantly enhance the local thermal uniformity without increasing the total energy consumption or prolonging the heating time.

The numerical findings were further examined by comparing them with an analytically derived lumped energy balance formulation, confirming the thermodynamic consistency and global energy conservation of the numerical model. Although this analytical validation does not replace direct experimental measurements, it provides a physically grounded verification of transient heating behaviour. Future work will focus on experimental validation using thermocouple measurements on a physical heating plate under controlled laboratory conditions to quantitatively confirm the predicted temperature distribution. More broadly, power-density balancing represents a general design principle for multi-element resistive heating systems where geometric symmetry does not ensure uniform heat flux.

Conflict of Interest

The authors declare no conflicts of interest.

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