Thermal, Exergy, and Environmental Performance Analysis of Modified Fin Geometries in Panel Radiators: A CFD-Based Study

Ayşe Bilgen Aksoy[1] (iD) , Fatma Nur Uzun[1] (iD) , and Yiğit Aksoy[2] (iD)

[1]Dept. of Energy Systems Engineering, Hasan Ferdi Turgutlu Faculty of Technology, Manisa Celal Bayar University, Manisa, Türkiye
[2]Dept. of Mechanical Engineering, Faculty of Engineering and Natural Sciences, Manisa Celal Bayar University, Manisa, Türkiye

Abstract: This study numerically investigates the thermal, exergy, and environmental performance of a widely used PCCP-type (Type 22) panel radiator equipped with three newly designed fin geometries using ANSYS-based CFD simulations. The proposed configurations were evaluated and compared with a conventional fin design under identical operating conditions to assess their influence on overall heat transfer performance. The results demonstrate that the I-profile fin achieved the highest performance, delivering a thermal efficiency of 61.9%, an exergy efficiency of 15.8%, and approximately a 33% reduction in CO_2 emissions compared to the standard model. While some alternative designs slightly reduced emissions further, they also resulted in notable exergy losses, highlighting a trade-off between energy quality and environmental benefits. These findings indicate that optimized fin geometries can be seamlessly integrated into existing manufacturing processes with minimal modifications, providing a practical and scalable solution for improving energy efficiency and supporting the development of sustainable radiator designs.

Keywords CFD Simulation, Panel Radiator, Fin Geometry, Thermal Performance, Exergy analysis, CO_2 emissions, Sustainable heating design, Energy efficiency

1. Introduction

The steady increase in global population and rapid technological advancements have led to a continuous rise in energy demand. Among various sectors, residential energy consumption ranks just behind industry and transportation in terms of total energy use (Ali et al., 2018). Therefore, improving the efficiency of heating systems in residential buildings plays a crucial role in ensuring both individual and national energy sustainability (Embaye et al., 2015).

Heating, ventilation, and air conditioning (HVAC) systems account for more than 30% of total energy consumption in Europe, 50% in the United States, and over 70% in the Middle East, indicating their significant impact on global energy use (Razmi et al., 2018). In Turkey, approximately 35% of total energy is consumed by buildings, and the energy required to heat one square meter of area is estimated to be 2–3

times higher than in EU countries (Sağbaş & Başbuğ, 2018). This makes the optimization of heating systems, particularly panel radiators that are commonly used in homes, a promising solution for improving energy efficiency without compromising indoor thermal comfort.

Panel radiators typically consist of flat, non-circular pipe sections that allow hot water to circulate. Since the water temperature is higher than the surrounding air, heat transfer occurs mainly through natural convection. Although commonly referred to as radiators, up to 80% of their total thermal output actually comes from convection, while only about 20% originates from radiation (Beck et al., 2004). Factors influencing the convective heat transfer of panel radiators include fin thickness, fin height, spacing between opposing fins, trapezoidal height, and edge radius. Previous studies have demonstrated that increasing the thickness and height of fins significantly enhances heat transfer performance (Calışır et al., 2019).

The performance of panel radiators is also affected by the thermophysical properties of their surroundings. For instance, a poorly insulated wall behind a radiator can reduce energy efficiency by nearly 5% (Robinson, 2016), while a roughened surface can improve convective heat transfer by up to 26% compared to smooth, polished surfaces (Shati et al., 2011). Conversely, long-term improvements using decorative elements, such as stone coverings in front of radiators, have been found to be ineffective (Menéndez-Díaz et al., 2014).

Several studies have investigated the influence of water flow rate and inlet temperature on radiator performance. For example, experiments using different convector types under varying flow rates and supply temperatures showed that the flow rate is the most critical factor affecting overall heat transfer, while the number of panels has a dominant effect on entropy generation (Geliş & Akyürek, 2021). Similarly, a study focusing on the development of modern panel radiators for low inlet water temperatures determined optimal combinations of inlet temperature and flow rate through ANSYS-based CFD simulations (Aydın, 2013).

The effect of airflow above radiators has also been analyzed using both CFD and particle image velocimetry (PIV) techniques. Results showed that, even when convector dimensions were altered, the airflow patterns above radiators remained consistent, indicating stable thermal comfort conditions (Calışır et al., 2021a). Due to standardization practices in Turkey, most panel radiator designs exhibit high similarity, resulting in only minor differences in thermal performance (Ekmekçi et al., 2014).

Some researchers have proposed fin design enhancements. For example, sweeping fins were reported to improve thermal efficiency by 32% compared to conventional models (Gheibi & Rahmati, 2019), while other studies recorded a 34% increase in total heat output by using modified baseboard radiator designs (Shobi et al., 2020). The effect of fin geometry has also been widely investigated. One study found that a triangular fin released 3.15% more heat than the standard model (Aydar et al., 2014). Furthermore, the placement of inlet and outlet connections plays a significant role in temperature distribution, with cross-flow configurations achieving better water distribution and more uniform thermal performance compared to parallel setups (Calışır et al., 2017).

In this study, unlike previous works, a widely used commercial PCCP-type panel radiator (Type 22) was selected. The influence of modified fin geometries on thermal performance was numerically evaluated and compared with a conventional fin configuration under identical operating conditions. Beyond thermal analysis, energy and exergy efficiencies were calculated, and the potential reduction in annual CO_2 emissions was estimated under typical residential heating scenarios. This multi-dimensional approach contributes to sustainable radiator design by quantifying both heat transfer enhancement and its broader environmental impact.

2. Physical Model and Geometric Configurations

2.1. General Overview of Panel Radiators

Panel radiators are widely used in residential heating systems because of their compact design, ease of installation, and cost-effectiveness. These systems typically consist of one or more flat panels through which

hot water circulates, enabling heat to be transferred primarily through natural convection. To improve convective heat transfer, thin metallic fins—commonly referred to as convectors—are integrated between the panels. The external assembly generally includes top and side covers, as well as connection fittings that allow seamless integration with existing plumbing systems (Figure 1).
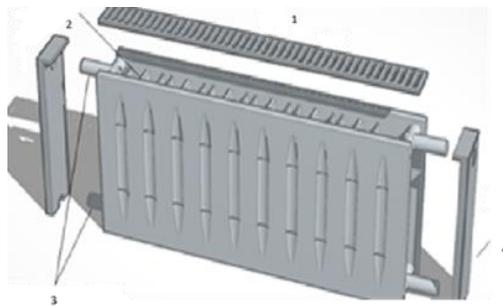
1	Top Cover
2	Convectors
3	Connection Fittings / Parts
4	Side Cover

Figure 1 Exploded view of a typical panel radiator with labeled components: convectors, top cover, side cover, and connection fittings

2.2 Flow Configurations in Panel Radiators

Panel radiators can be connected to the plumbing system using different configurations, depending on the desired thermal uniformity and installation constraints. The two most common connection types are:

- Parallel Connection (Figure 2): In this configuration, the inlet and outlet are positioned on the same side of the radiator. While this setup is easier to install, it can result in uneven temperature distribution, particularly in larger panels.
- Cross-Flow Connection (Figure 3): Here, the inlet and outlet are placed on opposite sides of the radiator. This arrangement enables the hot water to spread more uniformly across the radiator volume, which enhances heat transfer performance and ensures better thermal uniformity.
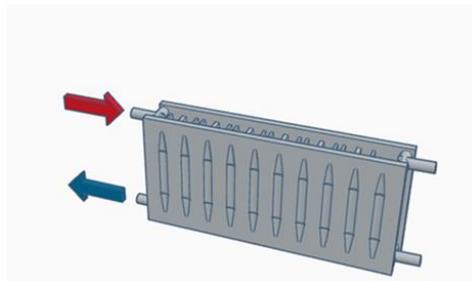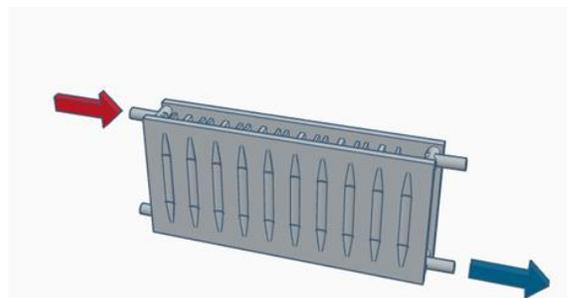

Figure 2 Parallel connection configuration   **Figure 3** Cross-flow connection configuration

2.3 Radiator Model Used in the Study

In this study, a Type 22 PCCP (panel–convector–convector–panel) panel radiator was selected for numerical analysis. This model consists of two water panels and two convector fins placed in between, creating a compact design with high heat transfer efficiency. The radiator geometry and operational parameters were determined in accordance with the TS EN 442 standards, and the key specifications are as follows:

Inlet temperature: 75 °C

Outlet temperature: 65 °C

Panel dimensions: 600 mm (height) × 600 mm (length) × 130 mm (depth)

Flow configuration: Cross-flow (inlet located at the top, outlet positioned at the bottom)

2.4 Material Properties and CFD Mesh Details

The panel material was selected as aluminum sheet metal, with a thickness of 1.2 mm in accordance with the DIN EN 10130 standard. The convector fins were assumed to be 0.5 mm thick. The working fluid was water, and a T-type pipe configuration with a diameter of 30 mm was used for water entry. The thermophysical properties of the materials employed in the simulations are presented in Table 1.
The main geometric specifications used in the CFD simulations are as follows:
- Panel height: 600 mm
- Panel length: 600 mm
- Panel depth: 130 mm
- Panel sheet thickness: 1.2 mm
- Convector fin length: 490 mm
- Distance between opposing fins: 30 mm
- Fin height: 50 mm
- Fin thickness: 0.5 mm
- Distance between two adjacent fins: 26 mm
- Fin base width: 13.74 mm
- Fin tip width: 13 mm
- Water channel spacing between opposite fins: 9.6 mm

Table 1. Thermophysical Properties of the Materials

Material	Density (kg/m³)	Dynamic Viscosity (Pa·s)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
Water	977.7	0.0004	0.6	4189.8
Aluminium	2719	—	202.4	871

2.5 Fin Geometry Designs

To enhance the thermal performance of the panel radiator, four different fin profiles were developed and evaluated through numerical simulations. Each fin was made of aluminum with fixed dimensions: 0.5 mm thickness, 26 mm width, and 50 mm length. Only the cross-sectional geometry was modified to assess its influence on convective heat transfer.
To evaluate the influence of fin geometry on the thermal efficiency of the panel radiator, three different fin designs were developed. In all cases, aluminum was used as the fin material, and the fin thickness (0.5 mm), width (26 mm), and length (50 mm) were kept constant. Only the cross-sectional profiles of the fins were modified, and the relevant geometric parameters are presented in Table 2.

Table 2. Fin Geometry and Material Specifications

Fin Material	Fin Thickness (mm)	Fin Width (mm)	Fin Length (mm)
Aluminum	0.5	26	50

The newly developed geometries are illustrated in Figure 4 (Fin-1), Figure 5 (Fin-2), and Figure 6 (Fin-3), while the conventional flat fin used for comparison is shown in Figure 7
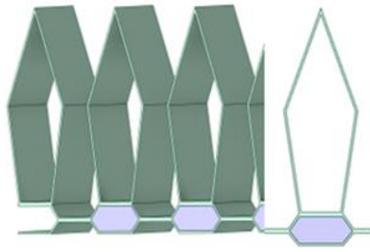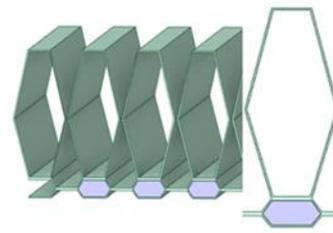
Figure 4 Cross-sectional geometry of Fin 1

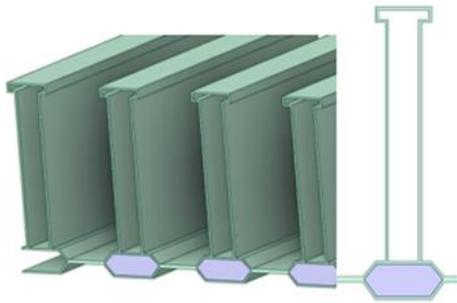**Figure 5** Cross-sectional geometry of Fin 2

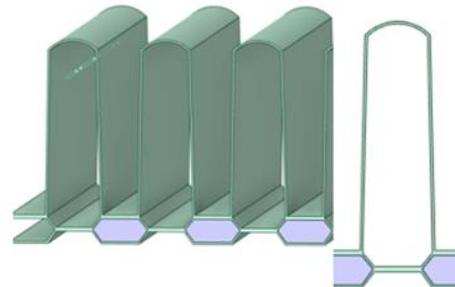**Figure 6** Cross-sectional geometry of Fin 3

Figure 7 Conventional Fin

Mesh quality in CFD (Computational Fluid Dynamics) directly affects the convergence and accuracy of the solution through parameters such as aspect ratio, skewness, and orthogonality. In thermal simulations involving natural or forced convection, maintaining a y^+ value below 5 and limiting skewness to under 0.9 are widely accepted standard practices (Versteeg, at all 2007).

In this study, a tetrahedral mesh structure was used, and prismatic layers were applied at the solid–fluid interfaces to resolve boundary layer effects. The mesh elements in the boundary layer were generated with a target y^+ value of 4 and a skewness of 0.840 to ensure geometrically optimal conditions. Additionally, a mesh independence test was conducted to verify that the selected mesh resolution does not significantly affect the simulation results.

3. Methodology

The methodology adopted in this study presents a holistic evaluation approach based on numerical analysis. Without conducting experimental studies, the thermal performance of the proposed radiator fin geometries was assessed using Computational Fluid Dynamics (CFD) simulations. In these simulations, the system behavior was modeled by incorporating analytical modeling results grounded in thermodynamic principles and validated using manufacturer-provided performance data. This integrated approach aims to enhance both the scientific validity and the real-world applicability of the findings.

In the first phase, CFD-based thermal analyses were performed for each proposed fin geometry, and the design offering the highest thermal efficiency was identified. This optimal design was then compared with a conventional panel radiator under identical operating conditions in terms of exergy efficiency and estimated CO_2 emissions. This step-by-step methodology enabled a comprehensive evaluation of the thermal, exergetic, and environmental performance of the improved design.

3.1 Thermal Analysis

Fins are extensively used to improve convective heat transfer by increasing the effective surface area available for energy exchange. Manufactured in various materials and geometries, these structures serve as key performance-enhancing elements, particularly in heat exchangers and thermal management systems where convection plays a dominant role.

In this study, a thermal analysis was conducted to evaluate the heat transfer performance of panel radiators equipped with different fin geometries. The impact of geometric variation on thermal efficiency was investigated using Computational Fluid Dynamics (CFD) simulations, following established numerical modeling approaches (Liu, 2023; Çengel, 2014).

The maximum heat transfer from a fin is assumed to occur when the entire fin is at the base temperature, and it can be calculated using the following expression (Incropera 2007)

$$Q_{fin,max} = h.A_{fin}.(T_b - T_\infty) \tag{1}$$

The maximum heat transfer from a fin is assumed to occur when the entire fin is at the base temperature, and it can be calculated using the following expression. In this formula, h represents the convective heat transfer coefficient (W/m²·K), A fin denotes the surface area of the fin (m²) ,T_b is the base temperature of the fin (typically corresponding to the wall or fluid temperature), and T_∞ refers to the ambient temperature.

The actual heat transfer from the fin can be determined by Equation (2), which accounts for the temperature gradient along the fin surface;

$$Q_{fin} = \dot{m}.c_p.(T_{in} - T_{out}) \tag{2}$$

In this equation $\dot{m}$ represents the mass flow mass flow rate of the fluid (kg/s), specific heat of the fluid (J/kg.K), fluid inlet and outlet temperatures.

The fin efficiency is defined as the ratio of the actual heat transfer from the fin to the maximum possible heat transfer, assuming the entire fin is at the base temperature. It is calculated by;

$$\eta_{fin} = \frac{Q_{fin}}{Q_{fin,max}} \tag{3}$$

In heating systems such as radiators, energy efficiency is defined as the ratio of the thermal energy output from the system to the total thermal energy input. This ratio indicates how effectively the system converts input energy into useful heating and is expressed by the following equation;

$$\eta_{thermal} = \frac{Q_{out(useful]}}{Q_{input}} \tag{4}$$

In the energy efficiency definition given in Equation 4, the input heat can be calculated using Equations 5 and 6, respectively

$$Q_{out(useful)} = \dot{m}.c_p.(T_{out} - T_{in}) \tag{5}$$

$$Q_{in} = \dot{m}.c_p.(T_{in} - T_\infty) \tag{6}$$

Exergy efficiency is a second-law-based performance indicator used to evaluate the effectiveness of thermal systems. As defined in Equation (7), it is calculated based on the outlet temperature of the system and the

dead-state (ambient) temperature. This metric represents the potential for system improvement and quantifies the fraction of available energy that can be converted into useful work (Bejan, 2016).

$$\eta_{exergy} = 1 - \frac{T_0}{T_{out}} \tag{7}$$

Carbon dioxide (CO_2) emission analysis is a commonly applied method for evaluating the environmental impacts of energy systems. In energy-consuming devices, CO_2 emissions are estimated based on the type of fuel used, the amount of energy consumed, and the emission factor associated with the energy source. This approach enables a comprehensive assessment of the environmental consequences arising from both the energy utilized and the energy saved through efficiency improvements (Dincer & Rosen, 2007). The total carbon dioxide (CO_2) emissions resulting from energy consumption can be estimated using the following equation

$$CO_2 = E.EF \tag{8}$$

where EEE represents the annual energy consumption (kWh/year), and $EFEF$ denotes the emission factor of the energy source (kgCO_2/kWh). This formulation is particularly suitable for systems with a known annual energy demand. However, for systems that operate only during specific periods of the year and where the instantaneous input energy is available, the CO_2 emissions can be calculated using the following equation:

$$CO_2 = \frac{Q_{input}.t.EF}{\eta_{system}.3600} \tag{9}$$

In this equation, the input energy refers to the thermal energy supplied to the system, ttt represents the annual operating time, and η denotes the thermal efficiency of the system. The emission factor (EF) corresponds to the amount of CO_2 emitted per unit of energy consumed (kgCO_2/kWh) and varies depending on the type of energy source used, such as natural gas, coal, or petroleum.

4. Result and Discoustion

In this study, detailed CFD simulations were performed for four different fin geometries, including one that represents the standard geometry commonly used in panel radiators. The resulting temperature distributions were carefully examined and comparatively analyzed to assess the thermal performance of each configuration. Figure 8 illustrates the temperature distribution of Fin 1 as obtained from the CFD simulations.
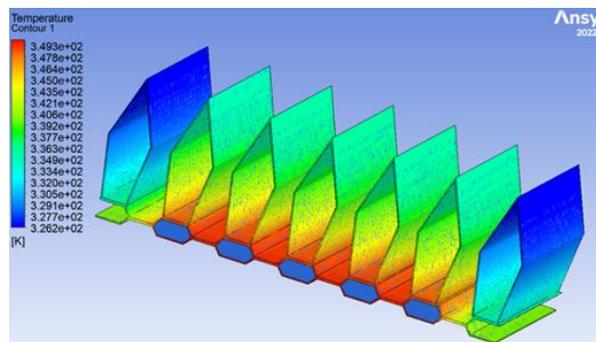

Figure 8 Temperature distribution of Fin 1 geometry (CFD results).

In the generated geometry, a noticeable temperature decrease from the base to the tip of the fin is observed, which is an expected behavior for surfaces where heat transfer occurs primarily through convection. The

base region, being in direct contact with the panel surface, exhibits the highest temperature, approximately 75 °C, where conduction dominates the heat transfer process. In contrast, at the tip region, where convective effects are more significant, the temperature decreases to around 53 °C. Although the fin geometry ensures a relatively uniform temperature distribution along the horizontal plane, heat losses occurring near the tip region reduce the overall fin efficiency.
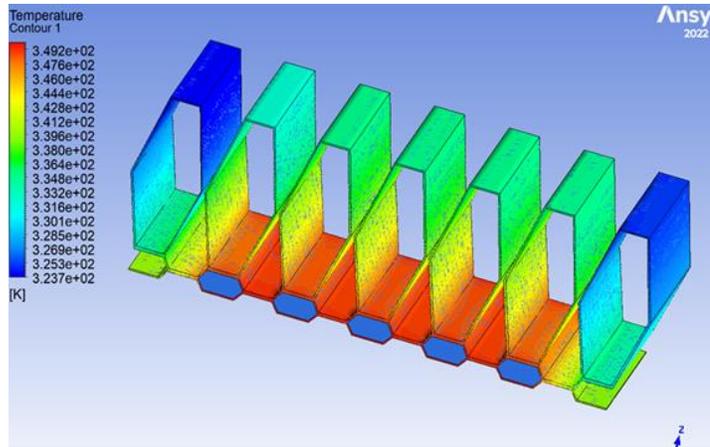

Figure 9 Temperature distribution of Fin 2 geometry (CFD results).

The temperature distribution for the Fin 2 geometry is presented in Figure 9. Similar to Fin 1, this design shows a base surface temperature of approximately 75 °C, which gradually decreases toward the tip region, reaching around 51 °C. However, the inclined transitions within the geometry introduce irregularities in the temperature distribution, which disrupt the uniformity of thermal conductivity along the fin. As a result, these variations contribute to a reduction in the overall fin efficiency. The temperature distribution for the Fin 3 geometry is illustrated in Figure 10.
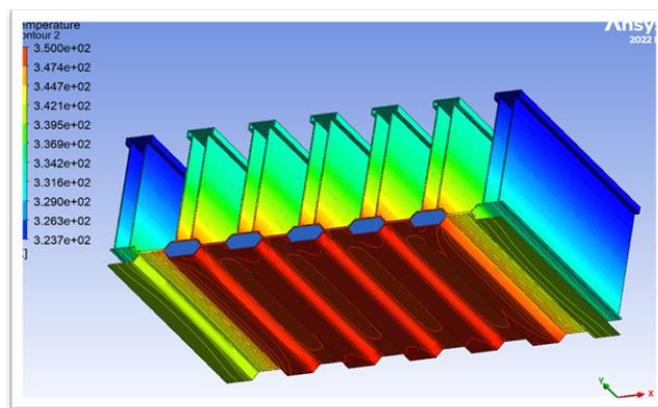

Figure 10 Temperature distribution of Fin 3 geometry (CFD results).

Fin 3 features a flat, sharp-edged structure designed in an "I-profile" configuration. Although the overall temperature distribution is similar to that of the other fins, it demonstrates a more uniform and symmetrical pattern. The absence of inclined surfaces within the geometry enhances symmetrical heat distribution and allows for more efficient heat conduction along the fin by reducing thermal resistance.
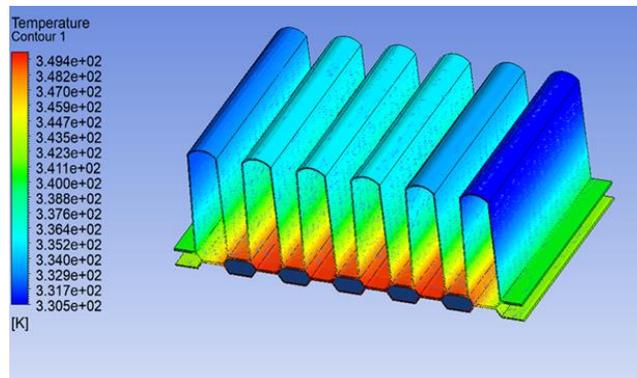
Figure 11 Temperature distribution of conventional fin geometry (CFD results)

Figure 11 presents the temperature distribution of the conventional (standard) fin geometry commonly used in panel radiators. Similar to the other geometries, the base region exhibits the highest temperature, while the temperature gradually decreases toward the fin tips due to the increasing thermal resistance along the fin height, reaching approximately 330 K (57 °C). The straight and thicker structure of this fin results in a more symmetrical temperature distribution across its surface.

In this study, fin efficiency, exergy efficiency, and CO_2 emission analyses were conducted for both the conventional and newly designed fin geometries, assuming an annual operating time of 1500 hours. The results of these analyses are summarized in Table 3.

Table 3 presents a comparative performance analysis between the standard (conventional) radiator fin commonly used in panel radiators and the newly designed fin geometries evaluated through Computational Fluid Dynamics (CFD) simulations.
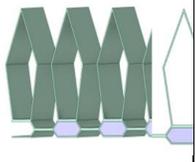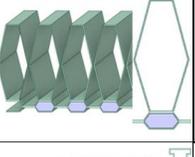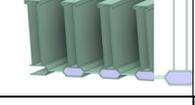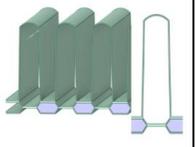
In terms of fin efficiency, the highest performance was achieved with Fin 3, yielding a value of 61.9%. This result indicates that Fin 3 enables more effective heat transfer by maintaining a uniform temperature distribution from the base to the tip. The fin efficiencies of the other geometries were relatively close, averaging around 48.3%.

For exergy efficiency, Fin 3 again demonstrated the highest performance, reaching 15.8%. In contrast, the lowest value was observed in Fin 2 at 7%, primarily due to its inclined and sharp-edged surfaces, which introduce additional geometric complexity and lead to greater exergy losses. The conventional fin and Fin 1 achieved exergy efficiencies of 13.3% and 14.6%, respectively. These results highlight that existing designs exhibit relatively low exergy efficiencies overall, indicating a potential performance enhancement of up to 80% through optimized geometries.

Regarding annual CO_2 emissions, Fin 2 recorded the lowest emission level at 46.57 kg/year, suggesting lower energy-related environmental impact. However, despite this advantage, Fin 2 also demonstrated poor thermal and exergy performance, indicating an inability to preserve energy quality. By comparison, Fin 3 produced slightly higher emissions (58.52 kg/year) but still represents a significant improvement—approximately a one-third reduction—compared to the conventional fin.

When considered comprehensively in terms of thermal performance, exergy efficiency, and environmental impact, Fin 3 (I-profile) stands out as the most efficient and sustainable design among all evaluated configurations.

Table 3 Comparison of Fin and Exergy Efficiencies with Annual CO_2 Emissions for Different Fin Geometries
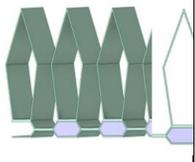
Fin		Fin Efficiency (%)	Exergy Efficiency (%)	Annual CO_2 Emissions (kg/year)
1		% 48,3	% 14.6	49,57
2		%48,2	%7	46,57
3		% 61,9	% 15,8	58,52
Conventional		%48,27	%13,3	44,95

5 Conclusions

In this study, alternative fin geometries were proposed and evaluated to enhance the heat transfer performance of panel radiators. Alongside the conventional fin structure, three newly designed fin profiles were analyzed using Computational Fluid Dynamics (CFD) simulations in ANSYS. For each configuration, thermal efficiency and temperature distribution were obtained, while exergy efficiencies and annual CO_2 emissions were also calculated. These comprehensive evaluations provide valuable insights for system designers in optimizing thermal performance, minimizing environmental impact, and improving system sizing.

Among the evaluated designs, the I-profile fin demonstrated the highest thermal and exergy efficiencies while maintaining an acceptable level of CO_2 emissions. This geometry offers an improvement potential of approximately 80% and can be seamlessly integrated into existing production processes with only minor modifications, making it a practical and scalable option for future manufacturing.

To fully exploit the potential of the improved design, it is recommended that the CFD results be validated through experimental studies. Such validation would not only support industrial adoption but also contribute to the development of future academic research in this field.

Future studies may focus on integrating the optimized I-profile fin geometry into low-temperature radiator systems, which are becoming increasingly relevant in modern energy-efficient buildings. Furthermore, additional research on material optimization and cost-effective manufacturing strategies could further enhance both performance and sustainability. By maintaining compatibility with current production processes, the proposed design provides a feasible, efficient, and scalable solution for the next generation of radiator technologies.

Declaration of Ethical Standards

As the authors of this study, we declare that he complies with all ethical standards. Technical editing and sentence structuring support were assisted by the ChatGPT language model developed by OpenAI.

Credit Authorship Contribution Statement

Ayşe Bilgen Aksoy: Investigation, Formal Analysis, Original Draft Preparation, Writing.
Fatma Nur Uzun: Methodology Development, Visualization, CFD Simulations.
Yiğit Aksoy: Resources, Validation, Review and Editing, Supervision

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

Funding / Acknowledgements

No funding declaration

Data Availability

No datasets were generated or analyzed during the current study.

References

Aydar, E., Ekmekçi, İ., & Şen, Y. (2014). Novel fin design for the panel type radiators using CFD. In Progress in Exergy, Energy, and the Environment (pp. 617–631). Springer, Cham.

Aydın, S. (2013). Düşük giriş suyu sıcaklıkları için yeni nesil panel radyatör geliştirilmesi (PhD Thesis). Bursa Uludağ University, Turkey.

Beck, S. M. B., Blakey, S. G., & Shati, A. K. A. (2004). A novel design for panel radiators. Applied Thermal Engineering, 24(8–9), 1291–1300.

Bejan, A. (2016). Advanced engineering thermodynamics (4th ed.). Wiley.

Calışır, T., Yazar, H. O., & Başkaya, Ş. (2017). Determination of the effects of different inlet–outlet locations and temperatures on PCCP panel radiator heat transfer and fluid flow characteristics. International Journal of Thermal Sciences, 121, 322–335.

Calışır, T., Yazar, H. O., & Başkaya, Ş. (2019). Thermal performance of PCCP panel radiators for different convector dimensions – An experimental and numerical study. International Journal of Thermal Sciences, 137, 375–387.

Calışır, T., Yazar, H. O., & Başkaya, Ş. (2021). Evaluation of flow field over panel radiators to investigate the effect of different convector geometries. Journal of Building Engineering, 33, 101600.

Çengel, Y. A., & Boles, M. A. (2015). Thermodynamics: An engineering approach (8th ed.). McGraw-Hill Education.

Dincer, I., & Rosen, M. A. (2007). Exergy: Energy, environment and sustainable development. Elsevier.

Ekmekçi, İ., Aydar, E., & Şen, Y. (2014). Panel tip radyatörlerin CFD yöntemiyle termal verim analizi. Proceedings of a National Conference.

Embaye, M., Al-Dadah, R. K., & Mahmoud, S. (2015). Thermal performance of hydronic radiator with flow pulsation – Numerical investigation. Applied Thermal Engineering, 80, 109–117.

Geliş, K., & Akyürek, E. F. (2021). Entropy generation of different panel radiator types: Design of experiments using response surface methodology (RSM). Journal of Building Engineering, 41, 102369.

Gheibi, A., & Rahmati, A. R. (2019). An experimental and numerical investigation on thermal performance of a new modified baseboard radiator. Applied Thermal Engineering, 163, 114324.

Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. (2007). Fundamentals of heat and mass transfer (6th ed.). John Wiley & Sons.

Koç, A., Yağlı, H., Koç, Y., & Uğurlu, İ. (2018). Dünyada ve Türkiye'de enerji görünümünün genel değerlendirilmesi. Mühendis ve Makina, 59(692), 86–114.

Liu, X. (2023). Analysis and optimization of radiator fin structure based on heat transfer efficiency. Journal of Physics: Conference Series, 2592(1), 012030. https://doi.org/10.1088/1742-6596/2592/1/012030

Menéndez-Díaz, A., Lorenzo, A., Álvarez, R., & Rodríguez, A. (2014). Thermal analysis of a stoneware panel covering radiators. Applied Energy, 131, 248–256.

Razmi, A., Soltani, M., Kashkooli, F. M., & Farshi, L. G. (2018). Energy and exergy analysis of an environmentally-friendly hybrid absorption/recompression refrigeration system. Energy Conversion and Management, 164, 59–69.

Robinson, A. J. (2016). A thermal model for energy loss through walls behind radiators. Energy and Buildings, 127, 370–381.

Sağbaş, A., & Başbuğ, B. (2018). Sürdürülebilir kalkınma ekseninde enerji verimliliği uygulamaları: Türkiye değerlendirmesi. European Journal of Engineering and Applied Sciences, 1(2), 43–50.

Shati, A. K. A., Blakey, S. G., & Beck, S. B. M. (2011). The effect of surface roughness and emissivity on radiator output. Energy and Buildings, 43(2–3), 400–406.

Shobi, M. O., Mahmoud, M. A., & El-Maghlany, W. M. (2020). Experimental and numerical investigations of a modified designed baseboard radiator using an air gap enhancing free convection heat transfer. Journal of Building Engineering, 32, 101535.

Versteeg, at all (2007).) An Introduction to Computational Fluid Dynamics: The Finite Volume Method   (2nd ed.). Pearson Education.