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# Synergistic Heat Transfer Enhancement In Backward-Facing Step Geometries Using Hybrid Nanofluids And Passive Geometric Modifications: A Comprehensive Review

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***Abstract***
*Backward-facing step (BFS) configurations have emerged as a critical focus in thermal engineering due to their widespread implementation in compact heat exchangers and microscale cooling systems. This review investigates recent developments in thermal enhancement strategies that combine hybrid nanofluids with engineered geometries to improve performance in BFS domains. Emphasis is placed on the thermal and hydrodynamic improvements offered by advanced nanoparticle blends, particularly copper oxide (CuO) and graphene, which demonstrate notable effects on flow recirculation, turbulence intensity, and heat transfer rates. Additionally, this paper examines how geometric elements such as embedded obstacles, modified channel surfaces, and structural deviations affect thermal behaviour based on insights from both computational and experimental literature. Critical metrics like Nusselt number enhancement, pressure drop variation, and thermal resistance reduction are explored in relation to flow conditions and nanoparticle parameters. The review concludes by outlining persistent knowledge gaps and suggesting directions for future research to refine and optimize BFS-based thermal systems using nanofluidic and geometric techniques.*
***Keywords***: *Backward-Facing Step (BFS), Hybrid Nanofluids, Geometric Obstacles, Corrugated Channel, Cuo–Graphene, Heat Transfer Enhancement*

## 1 INTRODUCTION

The growing global demand for energy-efficient technologies has catalyzed significant advancements in thermal system design, particularly in sectors such as microelectronics, automotive cooling, power generation, and solar thermal applications (Alsammarraie, Hashim, et al., 2023; Bahiraei & Ahmadi, 2018; Sidik et al., 2016; Zhang et al., 2019). In these systems, efficient heat dissipation is crucial for operational reliability and energy optimization. However, the limited thermal conductivity of conventional heat transfer fluids such as water, ethylene glycol, and mineral oils poses a major constraint on thermal performance, especially under high heat flux conditions (Ajeel et al., 2019; Zohuri, 2017).

To address this limitation, researchers have explored nanofluids engineered suspensions of nanoparticles within conventional base fluids as a promising alternative (Babar & Ali, 2019; Choi & Eastman, 1995; Ma et al., 2020). Nanofluids exhibit significantly enhanced thermophysical properties, including higher thermal conductivity, improved convective heat transfer, and greater specific heat capacity compared to traditional fluids (Alsammarraie, Ariffin, et al., 2023; Zohuri, 2017). These enhancements are largely attributed to the high surface area and thermal conductivity of nanoparticles, which promote more efficient microscale heat transfer mechanisms (Shaik et al., 2024; Sulaiman et al., 2020).

A wide array of nanoparticles has been investigated for their thermal performance. Metal oxides such as $Al_2O_3$, $TiO_2$, and CuO offer advantages in terms of chemical stability, cost, and ease of preparation (Sathish Kumar et al., 2023; Talib et al., 2022), while carbon-based materials like graphene and carbon nanotubes demonstrate exceptional thermal conductivity and mechanical strength due to their high aspect ratios and electron mobility (Bahiraei & Heshmatian, 2019; Shaik et al., 2024). Recent advancements have focused on hybrid nanofluids, which combine two or more nanoparticle types in a single base fluid to leverage synergistic effects that improve thermal performance, dispersion stability, and heat transfer efficiency beyond what mono nanofluids can achieve (Ahmad et al., 2022; Babar & Ali, 2019).

Among hybrid formulations, CuO–graphene nanofluids have emerged as a particularly effective combination. CuO contributes to chemical and structural stability, while graphene delivers extremely high thermal conductivity (Bahiraei & Heshmatian, 2019; Shaik et al., 2024). Several studies report that such hybrids significantly enhance convective heat transfer metrics, such as the Nusselt number and heat transfer coefficient, particularly in turbulent regimes (Omri et al., 2022).

Parallel to material innovations, passive thermal enhancement strategies that modify flow geometry without requiring additional energy have gained prominence. Configurations such as backward-facing steps (BFS), corrugated surfaces, ribs, and baffles introduce flow separation, reattachment, and vortex formation, which promote fluid mixing and heat transfer (Che Sidik et al., 2017; Jaffal, 2021; Xiao et al., 2020). The BFS geometry, in particular, is extensively utilized as a benchmark configuration for analyzing separated flow reattachment and convective enhancement (Chen et al., 2018; Selimefendigil & Öztop, 2015; Togun et al., 2014).

Recent studies confirm the significant potential of nanofluids, especially CuO- and graphene-based variants, in enhancing heat transfer when combined with geometric modifications. For instance, Omri et al. (2022) experimentally reported a 79.68% increase in heat transfer coefficient using CuO–graphene hybrid nanofluid in a vertical helical coil. Similarly, Q. Liu et al. (2023) and Korpyś et al. (2020) demonstrated 9.4% to 35% enhancement using CuO nanofluids in coiled exchangers. In backward-facing step (BFS) geometries, Cu-hybrid nanofluids achieved notable Nusselt number gains in numerical studies by Qi et al. (2021) and Nath & Murugesan (2022), highlighting synergistic effects between fluid and structure.

Despite these advancements, practical deployment of nanofluids particularly hybrid types still faces challenges. Long-term dispersion stability remains a key concern, as nanoparticles are prone to agglomeration and sedimentation during operation, especially under thermal cycling conditions (Bahiraei & Heshmatian, 2019; Shaik et al., 2024). Additionally, increasing nanoparticle concentration, while beneficial for thermal performance, often results in higher viscosity, leading to increased pressure drop and energy consumption (A. Hilo et al., 2018; Talib et al., 2022). Therefore, achieving an optimal balance between thermal enhancement and flow resistance is vital (Alsammarraie, Ariffin, et al., 2023).

Furthermore, modeling the behavior of nanofluids under turbulent and transitional flows requires robust turbulence models and accurate correlations for thermophysical properties (Abdollahpour et al., 2022; Selimefendigil & Öztop, 2017). Experimental data, however, is often inconsistent due to variability in nanoparticle properties, volume fraction, preparation methods, and test (Bahiraei & Heshmatian, 2019; Kherbeet et al., 2014). These discrepancies complicate comparative analysis and highlight the urgent need for standardized testing protocols (Poole et al., 2004; Zajec et al., 2021).

While separate bodies of research have extensively explored nanofluids or passive geometric enhancements, studies that investigate their combined impact particularly in backward-facing step (BFS) or corrugated wall configurations remain limited (Klazly & Bognar, 2022; Nath & Murugesan, 2022; Qi et al., 2021). Existing reviews often focus solely on numerical simulations or broadly generalize findings without isolating the performance of specific hybrid formulations such as CuO–graphene (Omri et al., 2022; Shaik et al., 2024). Moreover, many studies overlook essential comparative insights between experimental and numerical approaches and neglect key influencing factors, including nanoparticle morphology, magnetic field effects, and thermo-hydraulic stability (Nguyen et al., 2019; Roohani & Toghraie, 2022; Syed, 2025).

This review aims to bridge these knowledge gaps by systematically examining recent developments in the use of hybrid nanofluids within BFS and corrugated microchannel configurations with and without embedded geometric structures such as obstacles, ribs and baffles. The primary objective is to identify optimal combinations of working fluid composition and passive geometrical enhancements that maximize convective heat transfer while maintaining acceptable flow resistance. By synthesizing findings from both experimental and computational studies as shown in **Table 1**, this work provides a comprehensive framework for understanding the complex interplay between thermophysical properties and flow dynamics, offering guidance for future research in the design of compact, high efficiency thermal systems.

**Table 1: Studies on Hybrid Nanofluids in BFS and Corrugated Geometries**

| Author | Method | Nanoparticles | Base Fluid | Geometry | Enhancement |
|---|---|---|---|---|---|
| **Qi et al. (2021)** | Numerical Simulation | Cu/Ni (Hybrid) | Water | Backward-Facing Step (BFS) | ↑ Nusselt number with more step layers; hybrid nanofluids outperformed water; velocity most influential |
| **Nath & Murugesan (2022)** | Numerical (Galerkin FEM) | Cu–$Al_2O_3$ | Water | Backward-facing step channel | ↑ Nu avg by 38%, convective heat transfer ↑ by 20–40% |
| **Omri et al. (2022)** | Experimental | CuO–Graphene (80–20%) Hybrid | Water | Vertical Helical Coil Heat Exchanger | 23.65% ↑ in heat transfer coefficient (HTC) at 0.2% mass fraction; 79.68% ↑ at 1% mass; Max HTC = 1173 $W/m^2 \cdot K$ @ Re = 1843 |
| **Klazly & Bognar (2022)** | Numerical Simulation | $Al_2O_3$, $TiO_2$ (separately) | Water | Microscale Backward-Facing Step | ↑ Velocity and heat transfer with ↑ volume fraction; $Al_2O_3$ showed higher velocity/shear at 0.04 vol%; PEI decreased after certain vol% |
| **(Yousefi et al., 2023)** | Lattice Boltzmann Method | $Al_2O_3$ | Water | BFS Microchannel with ribs/dimples | ↑ Nusselt number by 63.64% (Re = 40) & 64.65% (Re = 100) with more ribs; ↑ by 54.54% (Re = 40) & 40.91% (Re = 100) with taller ribs |

## 2 Heat Transfer Mechanisms

Heat transfer proceeds by conduction, convection, and radiation. Convection plays the dominant role in practical systems and is categorized into natural, forced, and mixed convection. Natural convection is buoyancy-driven (Ahlers et al., 2018). Forced convection, especially in nanofluids under tube flows, significantly enhances heat transfer(Cieśliński & Kozak, 2023). Mixed convection, combining buoyancy and forced flow, is common in porous media systems (Amran et al., 2024).

A critical application of these thermal transport modes lies in heat exchangers, which facilitate energy transfer between working fluids across a wide array of sectors, including power generation, manufacturing, chemical processing, and refrigeration. The increasing need for compact and high-efficiency designs particularly plate-type configurations has driven innovations in this field (Tavousi et al., 2023; Zhang et al., 2019). Recent strategies have concentrated on enhancing internal fluid dynamics and optimizing surface characteristics to boost performance.

Passive enhancement methods such as implementing corrugated walls, internal fins, and ribs disrupt laminar flow and promote turbulence, thus increasing convective efficiency and reducing thermal (Abou Elmaaty et al., 2017; Ho et al., 2023) Structures like backward-facing steps (BFS) further stimulate vortex formation and recirculation zones, which intensify local heat transport (Selimefendigil & Öztop, 2015; Xiao et al., 2020) Additionally, nanofluids engineered by dispersing nanoparticles within conventional base liquids have shown remarkable potential for improving thermal conductivity and fluid behaviour. These advanced fluids are widely adaptable and provide significant enhancements over traditional coolants (Hajatzadeh Pordanjani et al., 2019; Zohuri, 2017).Their growing adoption underscores a transformative shift in both academic research and industrial thermal design, with ongoing developments expanding their role in next generation energy (Redhwan et al., 2016).

### 2.1 Classification and Function of Heat Exchangers

Heat exchangers are essential elements in thermal systems, enabling efficient thermal energy exchange between two or more fluid streams across a variety of engineering and industrial processes. Their classification is primarily based on factors such as flow arrangement, geometric compactness, constructional design, and the dominant heat transfer mechanism. Common categories include spiral, plate heat exchangers, and shell-and-tube as shown in Fig. 1, each tailored for specific operational conditions such as fluid properties, temperature levels, flow rates, and pressure constraints (Tavousi et al., 2023; Zohuri, 2017). Among these types, plate heat exchangers have attracted increasing attention due to their high thermal efficiency, compactness, and ease of cleaning and maintenance. Their modular and compact structure makes them ideal for systems with space limitations such as in renewable energy plants, HVAC/R applications, and industrial production facilities (Zhang et al., 2019). Their flexibility in configuration further supports customized integration into specialized thermal applications. The versatility of heat exchangers spans across a wide range of industries, including distillation, pasteurization, process heating and cooling, and thermal control in petrochemical and HVAC/R systems (Bahiraei & Ahmadi, 2018). Components like radiators, condensers, and cooling towers exemplify their practical usage in sectors such as manufacturing, electric power generation, and food processing, where precise thermal regulation is fundamental to performance and sustainability goals (Azeez mohammed Hussein et al., 2022).

To boost their effectiveness, modern designs often incorporate engineered surface geometries such as corrugated plates that enhance turbulence within the flow, thereby increasing convective heat transfer and lowering pumping energy requirements (Abou Elmaaty et al., 2017). Furthermore, the advent of nanofluids, characterized by their superior thermal conductivity relative to conventional fluids, represents a significant leap in heat exchanger technology. These fluids enhance thermal and hydraulic performance, contributing to increased system efficiency, compactness, and long-term reliability (Hajatzadeh Pordanjani et al., 2019; Zohuri, 2017).

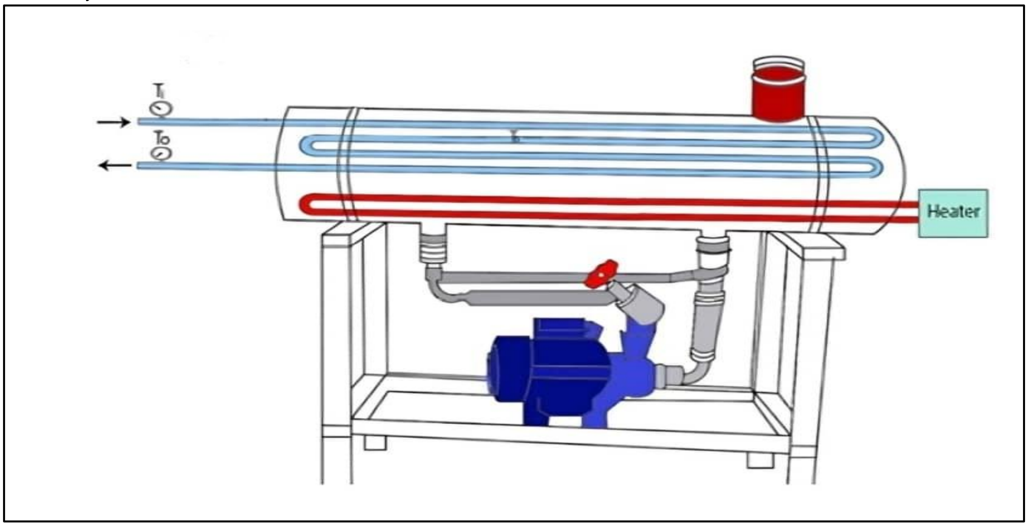


**Figure 1: Schematic of the apparatus shell-and-tube (Khouri et al., 2024)**

## 2.2 Limitations of Conventional Heat Exchangers and Emerging Enhancement Strategies

Conventional heat exchanger systems, despite their long-standing industrial adoption, present several technical constraints that limit their effectiveness under modern thermal management requirements. Among the most frequently encountered issues are excessive pressure drops, elevated thermal resistance, increased maintenance demands, and relatively poor heat transfer performance particularly under dynamic thermal loads or when subject to fluctuating energy inputs (Bahiraei & Ahmadi, 2018).These limitations not only compromise energy efficiency but also contribute to increased operating costs and hinder the integration of heat exchangers into compact, next-generation systems.

A critical limitation arises from the thermophysical inadequacies of traditional working fluids such as water, oil, and ethylene glycol. These fluids often exhibit low thermal conductivity and limited specific heat capacity, rendering them inefficient for high-performance or space-constrained applications (Zohuri, 2017).To mitigate these shortcomings, researcher's have increasingly turned to innovative thermal enhancement strategies aimed at improving heat exchanger effectiveness without introducing undue system complexity or high energy demand.

One of the most explored approaches is the implementation of passive enhancement techniques. These include the integration of corrugated surfaces, extended surfaces (fins), and internal flow disturbing structures such as ribs and baffles, which promote turbulence, enhance mixing, and reduce thermal

resistance. Collectively, these modifications significantly improve convective heat transfer while preserving the simplicity and reliability of the system (Abou Elmaaty et al., 2017; Xiao et al., 2020) .
In parallel, the incorporation of phase change materials (PCMs) has emerged as an effective thermal storage solution. PCMs provide latent heat capacity with minimal temperature fluctuation, thus enabling energy buffering and load levelling particularly in renewable energy applications where thermal intermittency is common (Diaconu et al., 2023).
A transformative development in this context is the application of nanofluids, which are engineered by dispersing nanoparticles into conventional base fluids. These advanced fluids offer substantially enhanced thermophysical properties, including improved thermal conductivity, higher heat capacity, and increased convective efficiency. As a result, nanofluids have become a promising solution to overcome the inherent limitations of traditional fluids and expand the operating range of heat exchanger technologies (Ahmad et al., 2022; Hajatzadeh Pordanjani et al., 2019).
The growing demand for compact, energy efficient, and high-performance thermal systems has also spurred research into active, passive, and hybrid enhancement strategies. While active techniques involve external control mechanisms or additional energy input, passive methods especially those based on nanomaterials and surface geometry modification are gaining prominence due to their simplicity, reliability, and low operational cost (Zhang et al., 2019).

## 3 Passive Enhancement Techniques

Passive heat transfer enhancement techniques improve heat exchanger performance by modifying surface geometry or flow paths to increase turbulence and disrupt thermal boundary layers. Unlike active methods, they require no external power and are cost-effective. Common approaches include fins, roughened surfaces, vortex generators, and nanofluids, which collectively enhance thermal efficiency while minimizing energy use, material costs, and system size. **Figure 2** illustrates passive and active techniques.

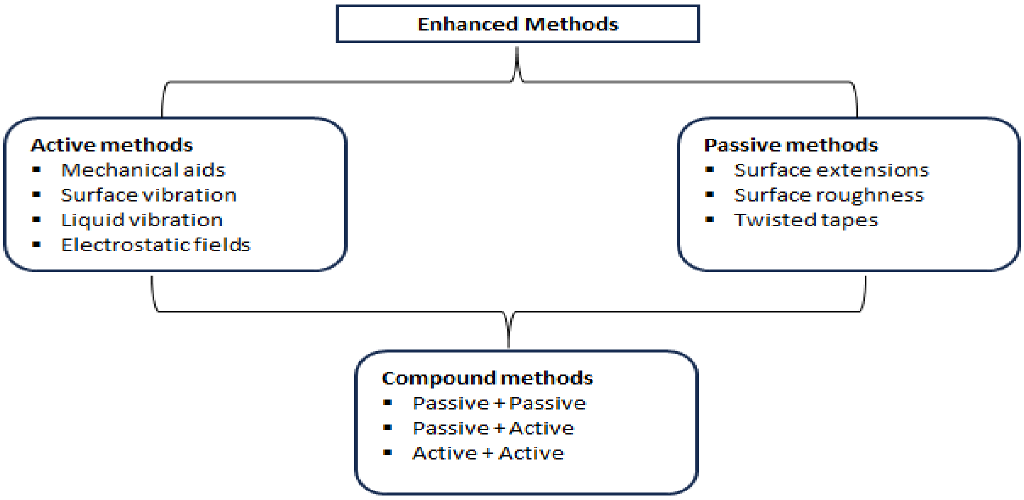


**Figure 2: Heat transfer enhancement techniques**
Source: (Che Sidik et al., 2017)

### 3.1 Corrugated Channels and Backward-Facing Steps (BFS)

Geometric modifications such as corrugated channels and backward-facing steps (BFS) are among the most effective passive techniques. Corrugated plate heat exchangers leverage surface undulations such as sinusoidal, trapezoidal, and V-shaped profiles to induce secondary flows, reduce boundary layer thickness, and increase effective heat transfer surface area. These geometries offer a practical balance between heat transfer enhancement and pressure drop, making them suitable for a range of industries, including food processing and energy systems (Abou Elmaaty et al., 2017; Jaffal, 2021; Kurtulmuş & Sahin, 2019).
In BFS geometries, the sudden expansion in the channel generates separated shear layers, recirculation zones, and reattachment regions. These flow patterns significantly impact local and average Nusselt numbers, with step height, expansion ratio, and Reynolds number being critical influencing parameters (Selimefendigil & Öztop, 2015; Togun et al., 2014) . Modifications such as integrating trapezoidal corrugations within BFS domains have been shown to further amplify thermal performance by enhancing vortex formation while controlling pressure losses (A. K. Hilo, Abu Talib, et al., 2020).

### 3.2 Internal Flow Disruptors: Ribs, Baffles, and Dimples

Passive devices such as ribs, baffles, and dimpled surfaces introduce artificial flow disturbances to promote mixing and enhance local heat transfer. V-shaped and inclined ribs are particularly effective in generating swirling secondary flows that reduce thermal resistance under high Reynolds number conditions (Xiao et al., 2020)(Taghreed et al., 2025). Similarly, as shown in **Table 2** porous and staggered baffle configurations contribute to better vortex stability and increased heat transfer rates (B. Wang et al., 2022; Zhu et al., 2022).

**Table 2: Different types of Extended Surface**

| Fin Type | Description | Shape |
|---|---|---|
| Rectangular Fins | Rectangular fins, straight or serrated, enhance heat transfer in exchangers due to large area, especially at low heat coefficients. |  |
| Triangular Fins | Triangular fins offer better heat transfer than rectangular fins but cause higher pressure drop and are harder to fabricate due to shape. |  |
| Circular Fins | Circular fins ensure uniform heat transfer across flow but increase pressure drop and fabrication complexity due to their round geometry. |  |
| Annular Fins | Annular fins dissipate heat efficiently in radial flow systems, suitable for compact areas but require precise manufacturing and ring-based mounting. |  |
| Pin Fins | Pin fins enhance heat transfer in limited spaces with minimal pressure drop, used in gas turbines; available in straight or curved arrays |  |
| Corrugated Fins | Corrugated fins expand surface area for improved heat transfer, commonly used in air-cooled exchangers, but involve complex fabricate |  |
| Perforated Fins | Perforated fins promote fluid mixing and reduce boundary layers, enhancing thermal performance but demanding precise, advanced manufacturing techniques. |  |
| Plate Fins | Plate fins are flat and simple, increasing area for better heat transfer in air-cooled exchangers, ideal for low heat transfer coefficients. |  |
| Tube Fins | Tube fins extend surface area on tubes, enhancing heat transfer in air or shell-and-tube exchangers, especially for low heat transfer cases. |  |

Source: (Hasan et al., 2023; Ho et al., 2023; Ji et al., 2015; Mohammed, 2017; Mohammed et al., 2017; Salman et al., 2020; Selimefendigil & Öztop, 2015, 2017).

Dimpled surfaces concave indentations engineered into heat transfer surfaces stimulate localized turbulence without incurring significant pressure drops. Their compactness and efficiency make them ideal for space constrained applications. When used in conjunction with high-performance nanofluids, these structures further elevate heat transfer capability (Suri et al., 2021).

Overall, the combined use of ribs, baffles, and dimpled structures illustrated in **Figure 3** presents a versatile and efficient passive strategy for thermal enhancement. Their adaptability allows for tailored geometric design based on system-specific requirements, making them suitable for various industrial applications from compact heat exchangers to complex cooling systems in gas turbines especially under thermally and hydrodynamically demanding conditions (Çelik & Erbay, 2021; J. Liu et al., 2022).

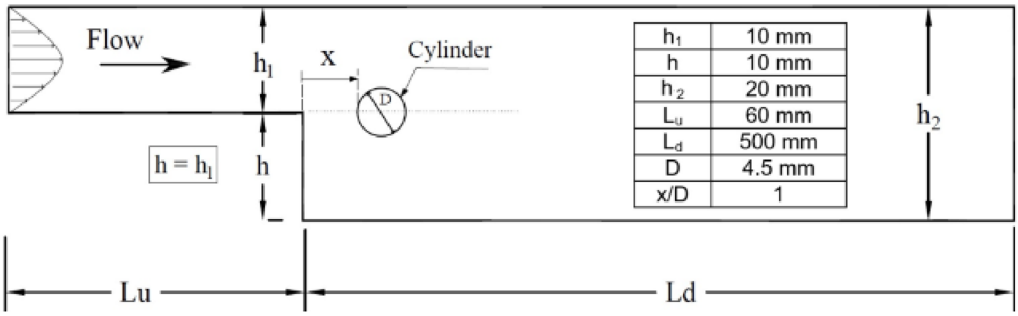


**Figure 3: Sketch of Backward-Facing Step Geometry with a Cylinder**
Source: (Abdollahpour et al., 2022)

### 3.3 Integration with Nanofluids

The integration of advanced nanofluids with passively modified geometries has shown considerable synergistic potential. Nanoparticles enhance thermal conductivity, while geometry-induced turbulence improves fluid mixing. For instance, MWCNT–Ag nanofluids achieved a 47.3% increase in thermal conductivity, while ternary blends like $Al_2O_3$–ZnO–MWCNT delivered up to 26.6% improvement at low volume fractions (Pourrajab et al., 2021). Likewise, BFS and corrugated configurations augmented with nanofluids demonstrated higher heat transfer rates than conventional systems ( Mohammed et al., 2017; Kherbeet et al., 2012).

### 3.4 Numerical and Experimental Validation

Extensive experimental and numerical investigations have established the effectiveness of passive heat transfer enhancement techniques particularly geometric modifications such as corrugations and obstacles, and the use of nanofluids in backward-facing step (BFS) and similar thermal systems. These methods have demonstrated significant improvements in thermal performance through induced vortex structures, enhanced recirculation, and increased surface area for heat exchange.

Numerical studies using Computational Fluid Dynamics (CFD) approaches, especially the Finite Volume Method (FVM) with algorithms like SIMPLE, have enabled detailed exploration of flow behavior, including reattachment lengths, vortex formation, pressure drop, and Nusselt number distributions in BFS geometries (A. K. Hilo, Abu Talib, et al., 2020; Koca, 2022). These studies reveal that trapezoidal and triangular corrugated walls significantly intensify mixing and local turbulence, resulting in heat transfer enhancements of up to 62% at low Reynolds numbers. Incorporating internal features such as baffles, porous inserts, or oscillating fins has also been shown to shift reattachment points and increase convective performance (Kumar & Vengadesan, 2019; Li et al., 2020).

Parallel experimental validations provide strong corroboration. Pereira & SchöNung (1983) and Javadi et al.(2018) demonstrated that variations in rib geometry, step height, or flow regime can lead to major changes in flow separation and entropy generation. For instance, triangular ribs induced the highest frictional irreversibility, while rectangular ones optimized thermal efficiency. In BFS configurations, obstacle-induced vortex disruption has been shown to enhance heat transport while maintaining acceptable pressure drops Wright & Rival (2013).

The synergy between passive techniques and nanofluids has further advanced this domain. Numerous studies have confirmed that dispersing nanoparticles such as CuO, $Al_2O_3$, MgO, graphene, and hybrid combinations in base fluids can significantly elevate thermal conductivity, Nusselt numbers, and overall heat transfer rates often exceeding 30–50% improvements under specific flow conditions (Amiri et al., 2016; A. K. Hilo, Talib, et al., 2020; Shaik et al., 2024). For example, experimental studies using CuO–graphene hybrids in BFS channels have recorded over 35% enhancement in thermal conductivity with modest increases in pressure drop, making them viable for microscale and high-temperature applications (Khouri et al., 2024; Talib et al., 2022).

Mixed convection scenarios, especially those involving magnetic fields or hybrid nanofluids, have also shown promise. Numerical work by Pekmen Geridönmez & Öztop (2021) and Inam & Lappa (2022) reveals that hybrid nanofluid flow under magneto-hydrodynamic influence can be strategically tuned to optimize heat transfer by altering recirculation zones and flow instabilities. These studies emphasize the interplay between Reynolds, Hartmann, and Richardson numbers in enhancing performance.

While discrepancies occasionally exist due to differences in turbulence models, nanoparticle types, or experimental setups Poole et al. (2004), overall consensus supports the effectiveness of combining passive geometric modifications with advanced nanofluid applications.

These results confirm that validated CFD simulations, aligned with a wide range of experimental studies, confirm that passive enhancement techniques including geometric modifications and the use of engineered nanofluids are highly effective in improving heat transfer performance. These findings strongly support the rationale for employing such integrated strategies in the present study to optimize thermal-hydraulic behavior in backward-facing step geometries

## 4 Nanofluids and Hybrid Nanofluids

### 4.1 Fundamentals and Classification

Nanofluids engineered colloidal suspensions of nanoparticles dispersed in base fluids such as water, oil, or ethylene glycol have redefined thermal management technologies through their superior thermal conductivity and convective heat transfer properties. Introduced by (Choi & Eastman, 1995). nanofluids have since attracted widespread attention for their potential in high performance applications, including power generation, electronic cooling, and renewable energy systems (Zohuri, 2017) .The suspended nanoparticles, typically less than 100 nm in diameter, can be composed of metals (e.g., Cu, Ag), metal oxides (e.g., $Al_2O_3$, $TiO_2$), carbon-based materials (e.g., CNTs, graphene), or hybrid combinations.

Thermophysical properties thermal conductivity, viscosity, density, and specific heat significantly impact nanofluid performance and must be optimized based on nanoparticle traits and application demands (Hemmat et al., 2015).

The thermophysical behaviour of nanofluids is significantly influenced by the type, size, shape, and dispersion stability of the particles. For instance, while smaller particles promote a larger surface area and more efficient thermal interaction, they are also more susceptible to agglomeration, which can reduce stability and effectiveness (Hemmat Esfe et al., 2015). Furthermore, non-spherical nanoparticles, such as rod- or blade-like structures, often demonstrate enhanced heat transfer performance due to intensified Brownian motion and interfacial interactions (Xie et al., 2002) .

Nanofluids are generally classified into mono-nanofluids, which contain a single type of nanoparticle, and hybrid nanofluids, which integrate two or more types. The latter offers a synergistic enhancement in both thermal conductivity and rheological behaviour (Ahmad et al., 2022; Ahmed et al., 2015). Ensuring colloidal stability is essential for sustaining the performance of nanofluids over time. Preparation techniques like ultrasonication and the use of surfactants are employed to ensure homogeneous particle distribution and to suppress agglomeration (Das et al., 2024). These enhancements are further modulated by nanoparticle concentration, flow regime, and fluid composition ( Tawfik, 2017).

### 4.2 Conductivity, Fraction, Size, Shape

The thermal performance of nanofluids is strongly influenced by key parameters including thermal conductivity, nanoparticle volume fraction, particle size, and shape. Thermal conductivity is often considered the most critical factor, as nanofluids inherently exhibit higher thermal conductivities than conventional working fluids such as water or ethylene glycol, resulting in enhanced convective heat transfer in advanced thermal systems (Yu & Xie, 2012; Zohuri, 2017). Nanoparticle volume fraction directly correlates with thermal performance; increasing the concentration of nanoparticles generally boosts conductivity due to the high intrinsic properties of the solid phase. However, excessive concentrations may lead to elevated viscosity, requiring higher pumping power and possibly reducing system efficiency thus highlighting the importance of optimizing this trade (Gupta et al., 2020; Hussein et al., 2014).

Particle size also exerts significant influence. Smaller nanoparticles offer a larger surface area-to-volume ratio, which promotes efficient thermal interaction. However, they are more prone to aggregation and sedimentation, posing challenges to colloidal stability (Chopkar et al., 2008; Hemmat Esfe et al., 2015) . In contrast, larger particles may improve dispersion stability but can reduce overall heat transfer rates.

Equally important is nanoparticle shape, which affects both heat conduction and flow characteristics. Non-spherical geometries such as rod-like, cylindrical, brick-shaped, or blade-shaped particles demonstrate superior thermal performance compared to spherical ones, primarily due to enhanced Brownian motion and increased interfacial interactions (Xie et al., 2002).

Recent experiments on water–ethylene glycol (50:50 vol%) nanofluids containing 0.025–0.1 vol% MWCNTs revealed thermal conductivity increases up to 6.4% at 50 °C, with enhancement correlated to nanoparticle volume fraction and temperature. The study also highlights that nanotube length, diameter (shape), and functionalization influence transport properties, while surfactant-assisted dispersion ensures fluid stability(Martin et al., 2025) . Despite these benefits, variations in size and shape can also alter other thermophysical properties such as viscosity, density, and specific heat capacity often increasing viscosity and density while reducing heat capacity (Abdullah et al., 2022). Hence, the optimization of these parameters is essential for tailoring nanofluids to specific engineering applications, ensuring a balance between thermal enhancement, flow efficiency, and long term stability.(Bhattad &Sarkar, 2021)reported brick-shaped hybrid nanoparticles yielded highest thermal performance factor in plate evaporators (see **Figure** 4).

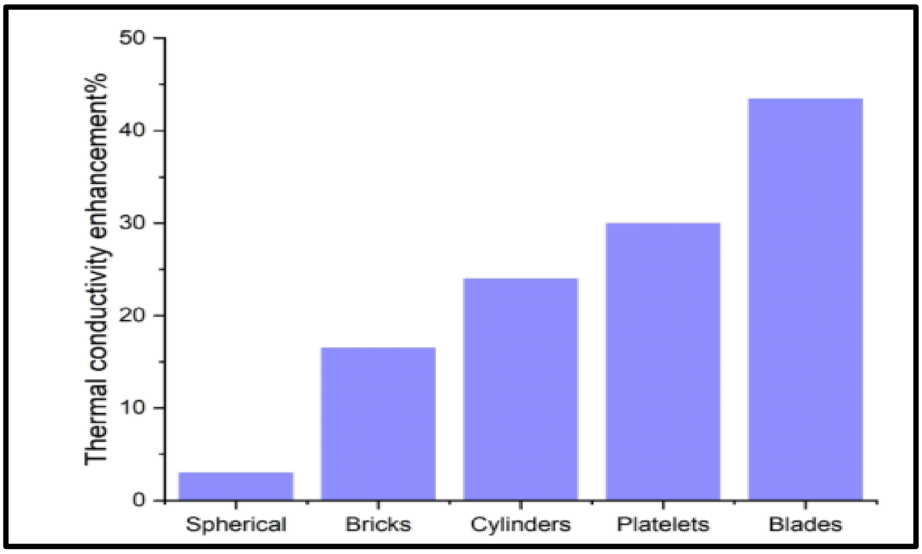


**Figure 4: Thermal performance factor for CuO-Cu hybrid fluid in different particle shapes**
Source : (Bhattad & Sarkar, 2021)

### 4.3 Hybrid Nanofluids Thermal Behavior

Hybrid nanofluids, engineered by suspending two or more types of nanoparticles in a base fluid, offer improved thermal and rheological properties compared to mono-nanofluids. These fluids leverage synergistic interactions between dissimilar particles like Ag, Cu, $TiO_2$, ZnO, and graphene to achieve enhanced thermophysical characteristics beyond those of single-particle systems(Ahmad et al., 2022; Ahmed et al., 2015) . This approach boosts conductivity, dispersion uniformity, and stability while minimizing agglomeration and sedimentation issues (Hajatzadeh Pordanjani et al., 2019; Zohuri, 2017) This synergy arises not merely from the sum of individual particle properties, but from enhanced inter-particle dynamics, thermal percolation pathways, and intensified Brownian motion, leading to superior energy transport phenomena (Mahian et al., 2019).CuO–graphene-based hybrids have demonstrated excellent performance, achieving high heat transfer rates at lower concentrations. These combinations enhance conductivity while keeping viscosity manageable, reducing the risk of pressure drop (Ahmad et al., 2022) . Furthermore, by adjusting variables such as nanoparticle type, size, shape, and mixing ratio, hybrid nanofluids can be tailored to meet the requirements of specific thermal applications, including geometrically complex systems like backward-facing steps (BFS) and corrugated microchannels.
By adjusting nanoparticle type, size, shape, and mixing ratio, hybrid nanofluids can be tailored to complex thermal applications such as backward-facing steps and corrugated microchannels. Their enhanced convective performance, reduced thermal resistance, and improved stability make them attractive for compact, high-efficiency systems like microchannel heat sinks, solar collectors, and industrial heat exchangers ( Ma et al., 2020; Maddah et al., 2018; Sajid & Ali, 2019).

### 4.4 Challenges: Stability and Viscosity

Despite the promising potential of nanofluids for enhancing thermal performance, practical implementation remains limited by two key challenges: dispersion stability and viscosity control. Ensuring a stable suspension of nanoparticles is particularly difficult, as particles tend to agglomerate, settle, or sediment over time, which undermines thermal conductivity and uniform fluid behavior (Hajatzadeh Pordanjani et al., 2019; Xu et al., 2006). Stability is influenced by factors such as particle size, shape, concentration, and material composition. While smaller nanoparticles offer a higher surface area and better thermal performance, they are also more susceptible to aggregation due to increased intermolecular forces (Chopkar et al., 2008; Hemmat Esfe et al., 2015), ultimately compromising homogeneity and heat transfer efficiency. This issue is clearly illustrated in **Figure 5**, as the tendency for clustering and uneven distribution is evident, highlighting the importance of effective dispersion techniques.

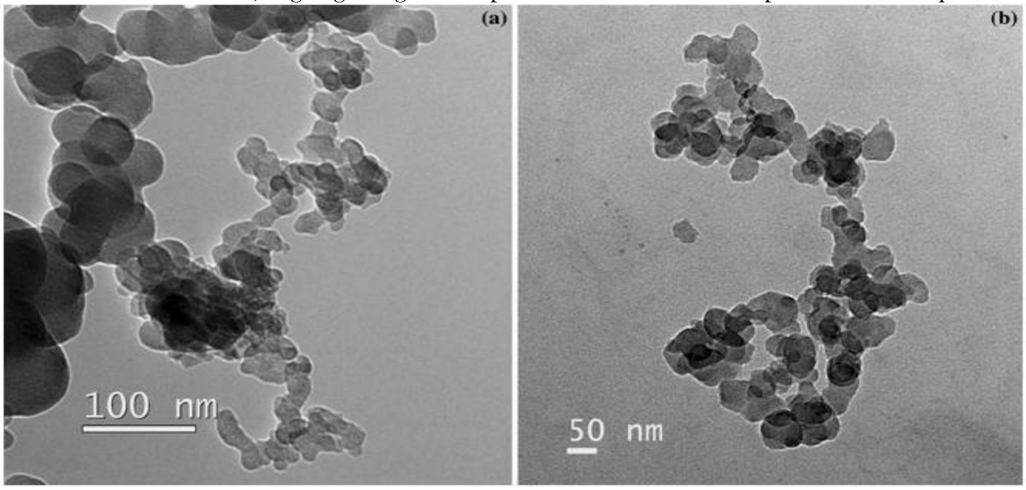


**Figure 5: TEM images showing nanometric Ag2Al powder particles suspended in (a) ethylene glycol and (b) water.**

Source: (Chopkar et al., 2008)

Equally critical is the viscosity increase associated with higher nanoparticle volume fractions. Although greater loading typically enhances thermal conductivity, it also raises flow resistance and pressure drop, leading to higher pumping power requirements particularly problematic in compact or high-throughput systems (Gupta et al., 2020; Hussein et al., 2014). These trade-offs are more pronounced in hybrid nanofluids, where multiple particle types can interact unpredictably, resulting in phase separation or irregular viscosity shifts (Ahmad et al., 2022; Ma et al., 2020).

To overcome these limitations, researchers advocate for advanced synthesis and stabilization methods, such as surfactant addition, surface functionalization, and ultrasonic dispersion, to improve both thermal conductivity and stability. Recent findings suggest that synergistic combinations of particle sizes, shapes, and materials play a vital role in optimizing hybrid nanofluid behavior across diverse thermal systems (Kalsi et al., 2025). Nonetheless, achieving predictable rheology and sustained dispersion remains a critical barrier to widespread industrial adoption (Sajid & Ali, 2018).

### 4.5 Nanofluid Applications in BFS and Microchannel Configurations

Nanofluids have proven effective in enhancing thermal performance in complex geometries like backward-facing steps (BFS) and microchannels, where conventional fluids underperform due to flow separation and spatial limitations. In BFS systems, nanofluids improve turbulence and thermal conductivity in shear layers, enhancing convective heat transfer (A. K. Hilo, Talib, et al., 2020; Kherbeet et al., 2012). Studies confirm significant increases in Nusselt numbers and reduced thermal resistance under turbulent flow and high Reynolds numbers.Hybrid nanofluids, such as CuO–graphene and $Al_2O_3$–$TiO_2$, provide superior thermophysical synergy, outperforming mono-nanofluids and demonstrating better performance evaluation criteria (PEC) in BFS contexts (Abedalh et al., 2021; Ahmad et al., 2022). In microchannel systems used in electronics cooling and microreactors nanofluids enhance heat flux and temperature uniformity, crucial for minimizing overheating and improving system longevity (Alsammarraie, Hashim, et al., 2023; Izadi et al., 2020). Even at low concentrations, they improve thermal performance with minimal pressure loss, supporting energy-efficient miniaturized designs. When combined with engineered microchannel surfaces (e.g., dimples, ribs, or corrugations), nanofluids benefit from induced vortices that boost mixing and thermal diffusion, yielding compact and efficient heat transfer solutions (Ekiciler et al., 2018; Jaffal, 2021) . Metal oxide nanofluids like CuO and $Al_2O_3$ have particularly shown high heat transfer coefficients, enabling compact exchanger designs for next-generation cooling systems (Salameh et al., 2023).

**Table 3** summarizes experimental and numerical studies on heat transfer in BFS geometries using mono and hybrid nanofluids (0.01%–5%), confirming Nusselt number enhancement and validating BFS with CuO–graphene nanofluids for thermal performance optimization in this study.

**Table 3: Summary of Studies on Nanofluids-Based Heat Transfer in BFS Geometries**

| No | Author(s) | Study Type | Geometry | Nanofluids | Findings |
|---|---|---|---|---|---|
| 1 | Selimefendigil & Öztop (2021) | Numerical | BFS with elliptic porous object | Hybrid (nano-diamond + $Fe_3O_4$ in EG-water, conc. not specified) | 33% heat transfer enhancement via geometry optimization; 28.4% via hybrid nanofluid; optimal Nu = 2.037 |
| 2 | Hilo et al.(2021) | Experimental | BFS channel | CuO-EG & MgO-EG (0–5%) | CuO-EG achieved 11% Nu increase at 5%; PEC = 1.5 (CuO), 1.2 (MgO); friction ↑ with conc. |
| 3 | (Mehrez & El Cafsi, 2019) | Numerical | BFS + magnetic field | Hybrid ($Al_2O_3$–Cu/water, 0.1–2%) | Nu enhanced, reattachment length decreased with concentration.; Hartmann number strongly influences regime |
| 4 | (Nath & Murugesan, 2022) | Numerical | BFS with inclined magnetic field | Hybrid (Cu–$Al_2O_3$/water, equal volume fraction) | Max Nu enhanced of 38% at 30° inclination; buoyancy and Hartmann number affect performance |
| 5 | (Abd Rahim et al., 2022) | Experimental | Microscale BFS | CuO/water (0–0.04%) | Peak PEC > 1 at 3% CuO; Nu ↑ with conc. and Re; friction ↑ with conc. |
| 6 | Pekmen Geridönmez & Öztop (2021) | Numerical | BFS + partial magnetic field | Hybrid (CuO–$Fe_3O_4$/water, 0.01–0.04%) | Strongest Nu gain with sinusoidal inlet; magnetite boosts heat transfer; weakest at step-centered field |
| 7 | (Karabulut & Alnak, 2021) | Numerical | BFS with/without chamfer | GO-DW (0.01%, 0.02%) | Nu enhanced by 11.7% and 14.33% at Re = 7500; chamfers enhanced TKE and flow |
| 8 | (Pournaderi & Aram, 2020) | Numerical | BFS channel | CuO (0.02%); compared with $TiO_2$, $Fe_3O_4$, etc. | $TiO_2$ gave highest Nu; CuO moderate; Nu enhanced and pressure drop increased with conc. and Re |
| 9 | Kherbeet et al. (2014) | Exp. & Num. | Microscale BFS | Water–$SiO_2$ & $Al_2O_3$ (0–1%); CuO (5%) referenced | $SiO_2$ gave highest Nu; $Al_2O_3$ had higher friction; numerical-experimental results matched (≤18.5% deviation) |

**5 Discussion**

A wealth of experimental and numerical studies has demonstrated the effectiveness of combining nanofluids with geometric modifications in enhancing heat transfer within backward-facing step (BFS) and corrugated channel systems. Various geometric configurations such as sinusoidal and trapezoidal corrugations, V-shaped ribs, baffles, and dimpled surfaces have proven successful in inducing turbulence, interrupting boundary layer development, and improving convective heat transfer rates (Jaffal, 2021; Xiao et al., 2020). These structural modifications are further complemented by the application of advanced nanofluids, particularly hybrid compositions like CuO–graphene and $Al_2O_3$–$TiO_2$, which offer superior thermal conductivity and thus contribute to significant increases in Nusselt numbers and overall thermal efficiency in both macro- and microscale domains (Abedalh et al., 2021; Ahmad et al., 2022).

Empirical studies consistently validate these enhancements, especially when nanoparticle concentrations are maintained within the range of 0.03 to 0.05 volume fraction. This range provides a favorable balance between thermal improvement and manageable pressure drop, optimizing the trade-off between performance and operational stability(Abu Talib & Salman, 2023; Amiri et al., 2016) . In tandem with experimental work, computational fluid dynamics (CFD) simulations offer a granular understanding of flow behavior, vortex generation, and thermal gradients, utilizing robust modeling techniques to replicate and extend experimental findings ( Hilo et al., 2020; Kumar & Vengadesan, 2019). These numerical tools also facilitate optimization of design parameters and nanofluid formulations, accelerating the development of highly efficient thermal systems.

This review integrates and synthesizes these findings to provide a comprehensive overview of recent progress in nanofluid-enhanced heat transfer and geometric modification strategies. The aim is to offer a structured reference for ongoing and future research efforts, serving as a valuable resource for both experienced researchers and newcomers. By highlighting key insights and best practices, the review underscores the synergistic benefits of combining passive geometry-based enhancements with high-performance nanofluids in next-generation heat exchanger applications.

**6 Limitation**

Despite considerable progress in enhancing heat transfer through nanofluids and geometric modifications, several critical limitations persist in the existing literature. A key shortcoming is the frequent reliance on isolated strategies such as the standalone application of corrugations, ribs, baffles, or nanofluids without adequately exploring their combined potential. This fragmented approach fails to capture the complex interactions between nanoparticle-induced thermal effects and geometry-driven flow behavior, thereby limiting the full realization of their synergistic benefits (Bouazizi & Turki, 2018).

Moreover, while many studies highlight improvements in Nusselt numbers and convective performance, they often overlook essential system-level factors such as pressure drop, pumping power, and overall hydraulic efficiency (Nawaz et al., 2012). These omissions can lead to an incomplete assessment of practical viability, particularly for compact or high-throughput applications where thermal and hydraulic performance must be balanced (Nogueira, 2022).

There is also a lack of consensus regarding optimal nanoparticle parameters including type, size, concentration, and hybrid ratios under varying Reynolds numbers and thermal conditions. Research on hybrid nanofluids remains underdeveloped and is frequently challenged by issues related to dispersion stability, reproducibility of thermophysical properties, and scalability of preparation methods (Ahmad et al., 2022; Hilo et al., 2020).

Although computational fluid dynamics (CFD) has been instrumental in visualizing flow and thermal behavior, many models depend on idealized assumptions, oversimplified boundaries, and turbulence approximations that may not accurately reflect experimental realities. These modeling constraints can limit predictive accuracy, especially in complex or transient geometries (Makahleh & Nassar, 2023).

Altogether, these gaps emphasize the need for comprehensive investigations that integrate nanofluid and geometrical enhancement strategies, supported by rigorous experimental validation, multi-objective optimization, and statistically robust methodologies. Future work should aim to develop holistic frameworks that evaluate both thermal and hydraulic performance under realistic operational conditions, ensuring practical relevance and industrial applicability.

**7 Future Research**

Future studies should adopt an integrated framework that examines geometric modifications alongside advanced nanofluid formulations to maximize thermal performance. Rather than isolating strategies, emphasis should be placed on hybrid setups like combining corrugated backward-facing step (BFS) geometries with hybrid nanofluids such as CuO–graphene, which leverage both turbulence and enhanced conductivity(Ahmad et al., 2022; Hilo et al., 2020). Such studies are vital to uncovering fluid structure interactions that improve system performance.

To address real-world demands, future research must incorporate hydraulic analysis including pressure drop, viscosity, and pumping power alongside thermal behavior. Using standardized metrics like the

Performance Evaluation Criteria (PEC) allows fair comparisons across different configurations. Investigating nanoparticle morphology, concentration, dispersion, and material synergy is also essential for improving conductivity while ensuring fluid stability and manageable flow characteristics. Machine learning (ML) and artificial intelligence (AI) can expedite design by predicting nanofluid performance across geometries and conditions. They can also aid in developing adaptive control for dynamic systems.

Moreover, validating these hybrid methods in applications like HVAC, electronics cooling, and solar collectors is crucial for industrial adoption (Bahiraei et al., 2018). In miniaturized systems such as microreactors and portable energy devices hybrid nanofluids integrated with microscale surfaces offer strong potential. For real-world use, future work should also emphasize long-term dispersion stability, life cycle analysis, and environmental impact assessments.

## 8 CONCLUSION

This paper has systematically examined the combined effects of geometric modifications and nanofluid technologies on heat transfer enhancement, particularly in backward-facing step (BFS) and corrugated channel configurations. Extensive experimental and numerical evidence supports the effectiveness of these dual strategies, demonstrating their potential in advancing thermal system performance across diverse applications.

Geometric modifications such as trapezoidal and sinusoidal corrugations, ribs, dimples, and internal obstacles consistently disrupt thermal boundary layers, induce flow instabilities, and promote vortex generation, thereby enhancing convective heat transfer. When these features are integrated with high-performance nanofluids, particularly hybrid compositions like CuO–graphene and $Al_2O_3$–$TiO_2$, the thermal performance is significantly amplified. These nanofluids exhibit superior thermal conductivity and consistently yield elevated Nusselt numbers, particularly at optimized volume fractions, which maintain a balance between enhanced heat transfer and manageable pressure drops.

Computational Fluid Dynamics (CFD) simulations further complement experimental findings by offering in-depth visualization and quantification of flow dynamics, heat distribution, and turbulence effects. These models not only validate empirical results but also facilitate parameter optimization and predictive design of thermal systems.

The synthesis of these findings underscores a critical insight: the synergistic integration of passive geometry-based enhancements with engineered nanofluids enables a new class of high-efficiency, compact heat exchangers. This dual-enhancement strategy is especially promising for advanced thermal applications in electronics cooling, aerospace systems, and microscale reactors, where space, energy efficiency, and reliability are paramount.

In conclusion, the convergence of passive geometric strategies and advanced nanofluid formulations represents a transformative approach to heat transfer engineering. This review provides a consolidated knowledge base to guide future research and industrial design toward thermally optimized, next-generation systems.

### REFERENCE

1.Abdollahpour, M., Gualtieri, P., & Gualtieri, C. (2022). Influence of a rigid cylinder on flow structure over a backward-facing step. Proceedings of the IAHR World Congress, 3989–3998. https://doi.org/10.3850/IAHR-39WC2521716X20221153

2.Abdullah, M. Z., Yu, K. H., Loh, H. Y., Kamarudin, R., Gunnasegaran, P., & Alkhwaji, A. (2022). Influence of Nanoparticles on Thermophysical Properties of Hybrid Nanofluids of Different Volume Fractions. Nanomaterials, 12(15). https://doi.org/10.3390/nano12152570

3.Abedalh, A. S., Shaalan, Z. A., & Saleh Yassien, H. N. (2021). Mixed convective of hybrid nanofluids flow in a backward-facing step. Case Studies in Thermal Engineering, 25. https://doi.org/10.1016/j.csite.2021.100868

4.Abou Elmaaty, T. M., Kabeel, A. E., & Mahgoub, M. (2017). Corrugated plate heat exchanger review. Renewable and Sustainable Energy Reviews, 70, 852–860. https://doi.org/10.1016/j.rser.2016.11.266

5.Abu Talib, A. R., & Salman, S. (2023). Heat transfer and fluid flow analysis over the microscale backward-facing step using βGa2O3 nanoparticles. Experimental Heat Transfer, 36(3), 358–375. https://doi.org/10.1080/08916152.2022.2039328

6.Ahlers, G., Grossmann, S., & Lohse, D. (2018). enard convection.

7.Ahmad, I., Faisal, M., Zan-Ul-Abadin, Q., Javed, T., & Loganathan, K. (2022). Unsteady 3D heat transport in hybrid nanofluid containing brick shaped ceria and zinc-oxide nanocomposites with heat source/sink. Nanocomposites, 8(1), 1–12. https://doi.org/10.1080/20550324.2021.2008208

8.Ahmed, M. A., Yusoff, M. Z., Ng, K. C., & Shuaib, N. H. (2015). Numerical investigations on the turbulent forced convection of nanofluids flow in a triangular-corrugated channel. Case Studies in Thermal Engineering, 6, 212–225. https://doi.org/10.1016/j.csite.2015.10.002

9.Ajeel, R. K., Salim, W. S. I. W., & Hasnan, K. (2019). Thermal performance comparison of various corrugated channels using

nanofluid: Numerical study. Alexandria Engineering Journal, 58(1), 75–87. https://doi.org/10.1016/j.aej.2018.12.009
10. Alsammarraie, H., Ariffin, M. K. A. M., Supeni, E. E., & Masuri, S. U. (2023). Numerical and Experimental Studies of the Nanofluid Characteristics that Effects on Heat Transfer Enhancement: Review and Comparison. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 107(2). https://doi.org/10.37934/arfmts.107.2.126
11. Alsammarraie, Hashim, Khairol, M., Mohd, A., Supeni, E. E., & Ujila, S. (2023). Numerical and Experimental Studies of the Nanofluid Characteristics that Effects on Heat Transfer Enhancement : Review and Comparison Journal of Advanced Research in Fluid Numerical and Experimental Studies of the Nanofluid Characteristics that Effects on. August. https://doi.org/10.37934/arfmts.107.2.126
12. Amiri, A., Arzani, H. K., Kazi, S. N., Chew, B. T., & Badarudin, A. (2016). Backward-facing step heat transfer of the turbulent regime for functionalized graphene nanoplatelets based water-ethylene glycol nanofluids. International Journal of Heat and Mass Transfer, 97, 538–546. https://doi.org/10.1016/j.ijheatmasstransfer.2016.02.042
13. Amran, M. F., Sultan, S. M., & Tso, C. P. (2024). A Comprehensive Review of Mixed Convective Heat Transfer in Tubes and Ducts: Effects of Prandtl Number, Geometry, and Orientation. Processes, 12(12). https://doi.org/10.3390/pr12122749
14. Azeez mohammed Hussein, H., Zulkifli, R., Faizal Bin Wan Mahmood, W. M., & Ajeel, R. K. (2022). Structure parameters and designs and their impact on performance of different heat exchangers: A review. Renewable and Sustainable Energy Reviews, 154. https://doi.org/10.1016/j.rser.2021.111842
15. Babar, H., & Ali, H. M. (2019). Airfoil shaped pin-fin heat sink: Potential evaluation of ferric oxide and titania nanofluids. Energy Conversion and Management, 202. https://doi.org/10.1016/j.enconman.2019.112194
16. Bahiraei, M., & Ahmadi, A. A. (2018). Thermohydraulic performance analysis of a spiral heat exchanger operated with water–alumina nanofluid: Effects of geometry and adding nanoparticles. Energy Conversion and Management, 170, 62–72. https://doi.org/10.1016/j.enconman.2018.05.061
17. Bahiraei, M., & Heshmatian, S. (2019). Graphene family nanofluids: A critical review and future research directions. Energy Conversion and Management, 196, 1222–1256. https://doi.org/10.1016/j.enconman.2019.06.076
18. Bahiraei, M., Rahmani, R., Yaghoobi, A., Khodabandeh, E., Mashayekhi, R., & Amani, M. (2018). Recent research contributions concerning use of nanofluids in heat exchangers: A critical review. Applied Thermal Engineering, 133(February 2017), 137–159. https://doi.org/10.1016/j.applthermaleng.2018.01.041
19. Bhattad, A., & Sarkar, J. (2021). Effects of nanoparticle shape and size on the thermohydraulic performance of plate evaporator using hybrid nanofluids. Journal of Thermal Analysis and Calorimetry, 143(1), 767–779. https://doi.org/10.1007/s10973-019-09146-z
20. Bouazizi, L., & Turki, S. (2018). Effect of Brownian motion on flow and heat transfer of nanofluids over a backward-facing step with and without adiabatic square cylinder. Thermophysics and Aeromechanics, 25(3), 445–460. https://doi.org/10.1134/S0869864318030113
21. Çelik, H. S., & Erbay, L. B. (2021). Heat transfer enhancement using different types of turbulators on the heat exchangers. Journal of Thermal Engineering, 7(7), 1654–1670. https://doi.org/10.18186/thermal.1025921
22. Che Sidik, N. A., Mahmud Jamil, M., Aziz Japar, W. M. A., & Muhammad Adamu, I. (2017). A review on preparation methods, stability and applications of hybrid nanofluids. Renewable and Sustainable Energy Reviews, 80, 1112–1122. https://doi.org/10.1016/j.rser.2017.05.221
23. Chen, L., Asai, K., Nonomura, T., Xi, G., & Liu, T. (2018). A review of Backward-Facing Step (BFS) flow mechanisms, heat transfer and control. Thermal Science and Engineering Progress, 6, 194–216. https://doi.org/10.1016/j.tsep.2018.04.004
24. Choi, S. U., & Eastman, J. A. (1995). Enhancing thermal conductivity of fluids with nanoparticles. American Society of Mechanical Engineers, Fluids Engineering Division (Publication) FED, 231, 99–105.
25. Chopkar, I., Sudarshan, S., Das, P. K., & Manna, I. (2008). Effect of particle size on thermal conductivity of nanofluid. Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, 39(7), 1535–1542. https://doi.org/10.1007/s11661-007-9444-7
26. Cieśliński, J. T., & Kozak, P. (2023). Experimental Investigations of Forced Convection of Nanofluids in Smooth, Horizontal, Round Tubes: A Review. Energies, 16(11). https://doi.org/10.3390/en16114415
27. Das, P. K., Santra, A. K., Ganguly, R., Dash, S. K., Muthusamy, S., Sha, M. S., & Sadasivuni, K. K. (2024). An extensive review of preparation, stabilization, and application of single and hybrid nanofluids. Journal of Thermal Analysis and Calorimetry. https://doi.org/10.1007/s10973-024-13449-1
28. Diaconu, B. M., Cruceru, M., & Anghelescu, L. (2023). A critical review on heat transfer enhancement techniques in latent heat storage systems based on phase change materials. Passive and active techniques, system designs and optimization. Journal of Energy Storage, 61, 106830. https://doi.org/10.1016/j.est.2023.106830
29. Ekiciler, R., Aydeniz, E., & Arslan, A. K. (2018). The effect of volume fraction of Sio2 nanoparticle on flow and heat transfer characteristics in a duct with corrugated backward-facing step. Thermal Science, 22, S1435–S1447. https://doi.org/10.2298/TSCI18S5435E
30. Gupta, M., Singh, V., & Said, Z. (2020). Heat transfer analysis using zinc Ferrite/water (Hybrid) nanofluids in a circular tube: An experimental investigation and development of new correlations for thermophysical and heat transfer properties. Sustainable Energy Technologies and Assessments, 39. https://doi.org/10.1016/j.seta.2020.100720
31. Hajatzadeh Pordanjani, A., Aghakhani, S., Afrand, M., Mahmoudi, B., Mahian, O., & Wongwises, S. (2019). An updated review on application of nanofluids in heat exchangers for saving energy. Energy Conversion and Management, 198. https://doi.org/10.1016/j.enconman.2019.111886
32. Hasan, M. F., Danışmaz, M., & Majel, B. M. (2023). Thermal performance investigation of double pipe heat exchanger embedded with extended surfaces using nanofluid technique as enhancement. Case Studies in Thermal Engineering, 43, 102774. https://doi.org/10.1016/j.csite.2023.102774
33. Hemmat Esfe, M., Karimipour, A., Yan, W. M., Akbari, M., Safaei, M. R., & Dahari, M. (2015). Experimental study on thermal conductivity of ethylene glycol based nanofluids containing Al2O3 nanoparticles. International Journal of Heat and Mass Transfer, 88, 728–734. https://doi.org/10.1016/j.ijheatmasstransfer.2015.05.010

34. Hemmat, M., Akbar, A., Arani, A., Rezaie, M., Yan, W., & Karimipour, A. (2015). Experimental determination of thermal conductivity and dynamic viscosity of Ag – MgO / water hybrid nano fl uid ☆. International Communications in Heat and Mass Transfer, 66, 189–195. https://doi.org/10.1016/j.icheatmasstransfer.2015.06.003
35. Hilo, A., Abu Talib, A. R., Nfawa, S. R., Sultan, M. T. H., & Abdul Hamid, M. F. (2018). Review of improvements on heat transfer using nanofluids via corrugated facing step. International Journal of Engineering and Technology(UAE), 7(4), 160–169. https://doi.org/10.14419/ijet.v7i4.13.21350
36. Hilo, A. K., Abu Talib, A. R., Acosta Iborra, A., Hameed Sultan, M. T., & Abdul Hamid, M. F. (2020). Effect of corrugated wall combined with backward-facing step channel on fluid flow and heat transfer. Energy, 190. https://doi.org/10.1016/j.energy.2019.116294
37. Hilo, A. K., Talib, A. R. A., Iborra, A. A., Sultan, M. T. H., & Hamid, M. F. A. (2020). Experimental study of nanofluids flow and heat transfer over a backward-facing step channel. Powder Technology, 372, 497–505. https://doi.org/10.1016/j.powtec.2020.06.013
38. Ho, M. L. G., Oon, C. S., Tan, L. L., Wang, Y., & Hung, Y. M. (2023). A review on nanofluids coupled with extended surfaces for heat transfer enhancement. Results in Engineering, 17. https://doi.org/10.1016/j.rineng.2023.100957
39. Hussein, Adnan M, & Kadirgama, R. A. B. K. (2014). Heat transfer augmentation of a car radiator using nanofluids. 1553–1561. https://doi.org/10.1007/s00231-014-1369-2
40. Inam, S., & Lappa, M. (2022). Hybrid forced-buoyancy convection in a channel with a backward facing step. International Journal of Heat and Mass Transfer, 194. https://doi.org/10.1016/j.ijheatmasstransfer.2022.122963
41. Izadi, M., Bastani, B., & Sheremet, M. A. (2020). Numerical simulation of thermogravitational energy transport of a hybrid nanoliquid within a porous triangular chamber using the two-phase mixture approach. Advanced Powder Technology, 31(6), 2493–2504. https://doi.org/10.1016/j.apt.2020.04.011
42. Jaffal, H. (2021). Augmentation of Fluid Flow and Heat Transfer Characteristics in corrugated Channel: A Review Study. Diyala Journal of Engineering Sciences, 14(1), 31–56. https://doi.org/10.24237/djes.2021.14104
43. Javadi, P., Rashidi, S., & Esfahani, J. A. (2018). Effects of rib shapes on the entropy generation in a ribbed duct. Journal of Thermophysics and Heat Transfer, 32(3), 691–701. https://doi.org/10.2514/1.T5298
44. Ji, W. T., Jacobi, A. M., He, Y. L., & Tao, W. Q. (2015). Summary and evaluation on single-phase heat transfer enhancement techniques of liquid laminar and turbulent pipe flow. International Journal of Heat and Mass Transfer, 88, 735–754. https://doi.org/10.1016/j.ijheatmasstransfer.2015.04.008
45. K. A. Mohammed, Talib, A. R. A., Nuraini, A. A., & Ahmed, K. A. (2017). Review of forced convection nano fl uids through corrugated facing step. Renewable and Sustainable Energy Reviews, 75(November 2016), 234–241. https://doi.org/10.1016/j.rser.2016.10.067
46. Kalsi, S., Kumar, S., Kumar, A., Alam, T., Sharma, A., & Singh, A. (2025). A review on hybrid nanofluids for heat transfer : advancements , synthesis , challenges and applications.
47. Karabulut, K., & Alnak, D. E. (2021). Investigation of Graphene Oxide-Distilled Water Nanofluids with Consideration of Heat Transfer and Flow Structure for Backward-Facing Step Flow. Journal of Engineering Thermophysics, 30(2), 300–316. https://doi.org/10.1134/S1810232821020119
48. Kherbeet, A. S., Mohammed, H. A., & Salman, B. H. (2012). The effect of nanofluids flow on mixed convection heat transfer over microscale backward-facing step. International Journal of Heat and Mass Transfer, 55(21–22), 5870–5881. https://doi.org/10.1016/j.ijheatmasstransfer.2012.05.084
49. Kherbeet, A. S., Mohammed, H. A., Salman, B. H., Ahmed, H. E., & Alawi, O. A. (2014). Experimental and numerical study of nanofluid flow and heat transfer over microscale backward-facing step. International Journal of Heat and Mass Transfer, 79, 858–867. https://doi.org/10.1016/j.ijheatmasstransfer.2014.08.074
50. Khouri, O., Goshayeshi, H. R., Mousavi, S. B., Hosseini Nami, S., & Zeinali Heris, S. (2024). Heat Transfer Enhancement in Industrial Heat Exchangers Using Graphene Oxide Nanofluids. ACS Omega, 9(22), 24025–24038. https://doi.org/10.1021/acsomega.4c02581
51. Klazly, M., & Bognar, G. (2022). Heat transfer enhancement for nanofluid flows over a microscale backward-facing step. Alexandria Engineering Journal, 61(10), 8161–8176. https://doi.org/10.1016/j.aej.2022.01.008
52. Koca, F. (2022). Numerical Investigation of Corrugated Channel with Backward-Facing Step in Terms of Fluid Flow and