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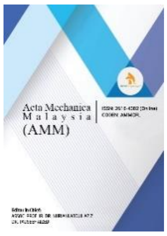

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REVIEW ARTICLE

ENHANCED HEAT TRANSFER OF NANOFLUIDS IN HORIZONTAL ANNULAR PASSAGES: A COMPREHENSIVE REVIEW

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ABSTRACT

This is a general overview of the recent advances in the area of the heat transfer improvement in horizontal annular passages through nanofluids with an emphasis on hybrid and mono-nanoparticle suspensions, as well as on several passive methods of enhancement. The review has summarized the results of ten recent research papers (2023-2025) that discuss various nanofluid configurations (e.g., GnP/MWCN, Alumina/Grapheme Oxide, f-MWCNT-Fe2O3), passage geometries (annular, doublepipe, corrugated), and how it can be enhanced (perforated fins, twisted tapes, magnetic fields, and the effect of nanoparticle sizes). It is suggested by the analysis that hybrid nanofluids can provide the best thermal performance, and that the geometric modifications, including noncircular inner rods and perforated fins, have a strong effect to maximize the convective heat transfer coaction. Some of the key findings point out those improvements can be made to a maximum of 94.03 percent in related systems, and direct studies of annular passages have been promising with optimized configurations. The morphological characteristics of 1D and 2D nanoparticles in the thermo-hydraulic performance are also stressed. The review ends with the determination of the most effective strategies and the description of future research in this crucial sphere of thermal engineering.

KEYWORDS

Nanofluids, Hybrid Nanofluids, Annular Passage, Heat Transfer Enhancement, Passive Techniques, Thermal Performance. Nanofluids, Annular Passage, Heat Transfer

1. Introduction

The need to have high efficiency heat transfer systems is ever growing in many industries such as, power generation industries, electronics cooling, and heating, ventilation and air conditioning (HVAC) systems. The two concentric tubes make up of annular passages are important elements of most heat exchangers, especially in the construct of the two pipes. Increasing the thermal performance of such passages is essential in order to decrease the size and operating cost of equipment. Nanofluids Colloidal suspensions of nanoparticles (usually 1-100 nm) in a base fluid (say water or oil) have become a revolutionary enhancement heat transfer medium because nanofluids have greatly enhanced thermal conductivity and coeffciency of convective heat transfer than the base fluid alone. Moreover, using combinations of nanofluids. using passive methods of enhancement, including altering the geometry of the flow, or the addition of inserts, is a synergist method to maximize thermal efficiency. This review is a centered comparison and synthesis of the recent studies (ten papers published between 2023-2025) that are associated with the utilization of nanofluid and other methods of enhancement, specifically within the framework of annular passages and the closely related geometries. This goal is to investigate systematically the methodologies, type of nanofluid, and key performance indicators of the chosen literature and determine promising directions of research and industrial use in the future.

2. Methodology

This review is based on a comparative analysis of ten selected research papers, all recently published (2023-2025), focusing on heat transfer enhancement using nanofluids. The papers were chosen to cover a range of nanofluid types, passage geometries, and enhancement techniques. Key data extracted from each study included the nanofluid composition, passage geometry, enhancement technique, methodology (experimental or numerical), and the reported heat transfer enhancement ratio. This information is summarized in Table 1 for structured

Table 1: Comparative Analysis of the Ten Selected Research Papers on Nanofluid Heat Transfer Enhancement

Ref.	Title (Year)	Nanofluid Type	Passage Geometry	Enhancement Technique
1	Computational analysis of turbulent flow characteristics... (2024)	Mono (1D MWCNTs and 2D GNPs)	Not Specified (Turbulent Flow)	Comparison of Nanoparticle Dimensions (SSA and ODs)

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Table 1: Comparative Analysis of the Ten Selected Research Papers on Nanofluid Heat Transfer Enhancement

2	Effect of nonuniform wall corrugations... (2023)	Hybrid (GnP/MWCNwater)	Rectangular Corrugated Tube	Non-uniform Wall Corrugations (PWC)
3	Numerical investigation of thermohydraulic performance... (2023)	Mono (Clovetreated GnP)	Annular Passage with Fins	Perforated Curve Fins
4	Heat transfer enhancement of the f-MWCNTFe2O3/Water... (2024)	Hybrid (fMWCNTFe2O3/Water)	Circular Tube	Wire Coil + Perforated Twisted Tape
5	Thermal performance assessment of alumina/graphe ne oxide... (2024)	Hybrid (Alumina/Graph ene Oxide)	Annular Passage (Multiple Configurations)	Multiple Annular Configurations
6	Experimental and Computational Fluid Dynamic CFD Analysis... (2023)	Mono (GNP/Water)	Double-Pipe Heat Exchanger (Annular)	None (Focus on Nanofluid)
7	Heat transfer inside annular passages: A comparison of non-circular... (2023)	Mono (Ecofriendly graphene nanofluid)	Annular Passage (Noncircular)	Non-circular Inner Rod (Pentagonal)
8	Experimental study on the thermal performance of hybrid nanofluid... (2025)	Magnetic Hybrid (Fe3O4/water)	Compact Plate Heat Exchanger	Magnetic Field
9	Modeling of turbulent flows through annuli with smooth and rough walls; drag reduction and heat transfer ... (2024)	None(Conventional Fluid/Polymer Solution)		
10	An Experimental CFD Analysis of Heat Transfer Enhancement in Radiator Tube using Hybrid Nanofluid... (2025)	Hybrid nanofluid	Raditor Tube (Circular Tube)	None (Focus on nanofluid)

3. Results and Discussion

3.1 Heat Transfer Enhancement Comparison

Figure 1 provides a visual comparison of the maximum heat transfer enhancement ratios reported in the papers that provided a specific percentage value. This chart highlights the exceptional performance of the f-MWCNT-Fe2O3/Water hybrid nanofluid in Ref. 4, which achieved the highest enhancement at 94.03%, although the study was conducted in a circular tube with complex internal inserts. The chart also shows that mono nanofluids (as in 1 and 7) achieve significant improvements, especially when combined with optimized nanoparticle morphological characteristics (23.25% in) .

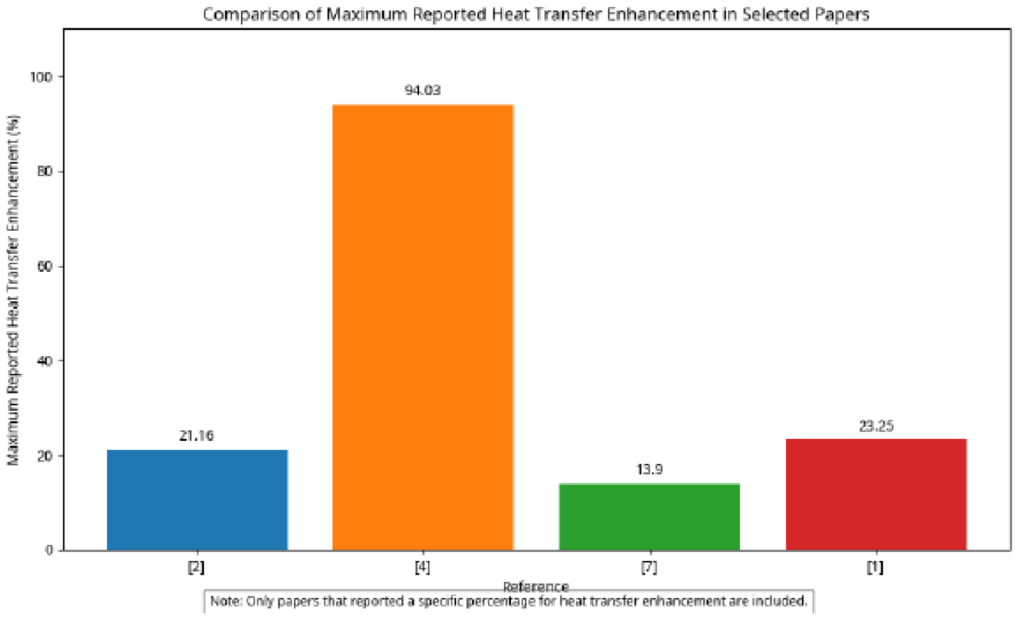

Figure 1: Comparison of Maximum Reported Heat Transfer Enhancement in Selected Papers.

3.2 Nanofluid Composition: Hybrid vs. Mono

The reviewed literature shows a clear trend toward using hybrid nanofluids for superior thermal performance. Four of the ten papers 2,4,5 and 8 utilized hybrid compositions, combining materials such as graphene nanoplatelets (GnP) with multi walled carbon nanotubes (MWCN) 2 , or Alumina with Graphene Oxide 5 .

The rationale behind this lies in the synergistic effect of combining two or more nanoparticle types, which can lead to enhanced thermal conductivity and stability. For instance, the study in Ref 8 , although conducted in a plate heat exchanger, explicitly reported that the hybrid nanofluid provided superior enhancement compared to its mono-nanofluid counterpart, especially under the influence of an external magnetic field. Similarly, the 9f-MWCNT-Fe2O3/Water) hybrid nanofluid in Ref 4. achieved the highest reported enhancement, ranging from 32.31% to an impressive 94.03%. In contrast, studies using mono nanofluids1,3,6 and 7 showed significant improvement, particularly those employing graphene-based materials (GnP, Clove-treated GnP). However, the highest enhancement reported in direct annular passage studies using mono nanofluids was 13.9% 7 , suggesting that while mono nanofluids are effective, hybrid compositions often yield higher performance gains.

3.3 Geometric, External Field, and Particle Morphology Enhancement Techniques

The review highlights the critical role of passive enhancement techniques alongside nanofluids, in addition to the importance of nanoparticle morphological characteristics. The studies can be broadly categorized into:

- Direct Annular Passage Modification: Papers focus directly on annular geometry. Ref. specifically investigates heat transfer enhancement in a radiator tube, which is a type of annular passage, using hybrid nanofluids and CFD analysis. Ref. showed that changing the inner rod shape from circular to pentagonal resulted in a 13.9% increase in heat transfer due to flow disturbance and secondary flow generation. Ref. investigated the use of perforated curve fins within the annular passage, a technique aimed at increasing the heat transfer surface area and inducing swirl. Ref. explored multiple configurations of the annular passage itself, demonstrating the importance of geometry optimization. Furthermore, Ref. explored the modeling of turbulent flows through annuli with smooth and rough walls, highlighting the trade-off between drag reduction and heat transfer enhancement, and the importance of wall roughness in influencing both aspects.

- Related Geometries and High-Impact Inserts: Papers use related geometries (corrugated tubes or circular tubes with internal inserts). Non-uniform wall corrugations (PWC) in Ref. achieved a 21.16% increase in Nusselt number,demonstrating the effectiveness of flow disturbance in confined spaces. The most dramatic enhancement (up to 94.03%) was achieved in Ref. by combining a wire coil with a perforated twisted tape, a technique that generates intense swirl and mixing, albeit in a simple circular tube, which is a valuable benchmark for annular insert design.

- External Field Enhancement: Ref. introduced an external factor, the magnetic field, to enhance the performance of a magnetic hybrid nanofluid (Fe_3O_4/water). Although the geometry was a compact plate heat exchanger, the concept of using external fields to control the flow and thermal properties of magnetic nanofluids is highly relevant to annular passages, especially in applications requiring dynamic control over heat transfer. 4. Effect of Nanoparticle Morphological Characteristics: The new paper provided a computational analysis of the turbulent flow characteristics of nanofluids containing 1D (MWCNTs) and 2D (GNPs) carbon nanomaterials (Tao, H., et al., 2024). The results showed that 2D nanoparticles (GNPs) with a larger specific surface area (SSA) (GNPs-750) achieved the highest heat transfer enhancement of 23.25%, confirming that the choice of nanofluid depends not only on the material, but also on its shape and dimensions. This finding is crucial for designing optimal nanofluids for use in annular passages.

3.4 Comparison of Methodologies

The studies utilized a mix of numerical (CFD) and experimental methodologies, with paper 9 adding to the numerical analysis of annular passages:

- Numerical (CFD): Papers 1,2,3 and 7 relied on numerical simulation, which is essential for optimizing complex geometries (like perforated fins 3 or non-circular rods 7), studying the effect of subtle fluid properties (like particle dimensions), and analyzing the impact of wall roughness on turbulent flows in annuli 9 before costly experimental verification (Tao, H., et al., 2024).

- Combined Numerical and Experimental: Papers 5 and 6 used a combined approach, which is the most robust. Ref. 6 used CFD to validate experimental results for GNP/water in a double-pipe heat exchanger (annular passage), while Ref. 5 used both methods to assess the performance of the Alumina/Graphene Oxide hybrid nanofluid in multiple annular configurations.

- Experimental: Papers 4and 8 were purely experimental, providing high-fidelity data on the actual performance of enhancement techniques and hybrid nanofluids. The trend suggests that future research in annular passages should prioritize the combined numerical and experimental approach to ensure both theoretical optimization and practical validation of proposed enhancement strategies, with a focus on accurate modeling of nanoparticle characteristics as in Ref. 1 .

3.5 Visual comparison between corrugated tube and annular passage:

Figure 2: Comparison between corrugated tube and annular passage.

Table 2: Comparison between corrugated tube and annular passage.

Corrugated Tube	Annular Passage	Feature
Higher: More stable and uniform temperature distribution along the flow direction	Lower: Presence of distinct cold spots at reattachment points and warmer zones in recirculation areas	Thermal Uniformity
''Continuous'' Cooling: Steady heat dissipation across the extended surface area (fins)	''Aggressive'' Cooling: Intense heat removal concentrated at the corrugation peaks/impact points	Transfer Efficiency
Functions as a thermal bridge/carrier between the internal fins and the bulk fluid	Acts as a heat dissipater within the vortex and recirculation zones behind corrugations	Nanofluid Role

4. Optimized Heat Exchange System Corrugated Tubes + GNP/MWCNT Nanoflouid

Based on the research findings (such as in Papers 1 and 2), the system operates as follows:

Rapid Absorption: The hybrid nanoparticles capture heat from the tube wall with extreme speed

Efficient Distribution: Due to the "turbulence" generated by the corrugations, these heated particles are rapidly mixed with the rest of the fluid in the center of the tube

Maximum Efficiency: This integration significantly boosts the Nusselt Number (Nu), leading to cooling rates up to 60% higher than traditional systems while maintaining stability through chemical functionalization (as noted in Papers 3 and 7).

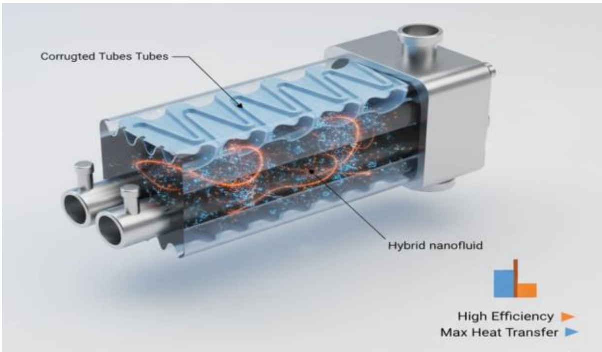

Figure 3: Optimized Heat Exchange System Corrugated Tubes + GNP/MWCNT Nanoflouid

5. Conclusion and Future Directions

This review confirms that the use of nanofluids, particularly hybrid compositions, is a highly effective strategy for enhancing heat transfer in annular passages and related heat exchanger geometries. The analysis also highlights the importance of considering fluid dynamics aspects like wall roughness in turbulent flows, and the application of hybrid nanofluids in radiator tubes. Key findings are:

- Hybrid Nanofluids are Superior: Hybrid nanofluids (e.g., GnP/MWCN, f-MWCNT-Fe2O3) consistently show the potential for higher heat transfer enhancement compared to mono nanofluids, with reported increases reaching 94.03% 4 .
- Geometric Modification is Crucial: Passive techniques that induce flow disturbance and swirl, such as non-circular inner rods 7 and perforated fins 3 , are essential for maximizing the convective heat transfer coefficient within the annular space.
- Nanoparticle Morphological Characteristics Matter: Recent research has shown that the dimensions and shape of nanoparticles (1D vs. 2D) significantly impact thermohydraulic performance, opening the door for micro-level optimization of nanofluids.
- External Fields are a Promising Avenue: The application of external fields, such as the magnetic field in Ref. 8 , provides a novel and controllable way to enhance the thermal performance of magnetic nanofluids.

Future Research Directions:

Based on the analysis, the following areas warrant further investigation:

- Dual Optimization: Future research should focus on combining the best hybrid nanofluids (such as those analyzed in 4 and 5) with

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optimal annular passage geometric modifications (such as those analyzed in 3 and 7), while considering the morphological characteristics of the nanoparticles and the impact of wall roughness on turbulent flows 9 .

- Thermo-hydraulic Performance Index (TPI): Future work must consistently report the Thermo-hydraulic Performance Index (TPI) to provide a balanced assessment of heat transfer gains versus the associated pressure drop penalty, a critical factor for practical application.

Dynamic Enhancement Techniques: Further exploration of external fields (magnetic, electric) combined with ferro-nanofluids in annular passages is needed to develop dynamically controllable heat transfer systems.

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