NTU Journal of Engineering and Technology (2025) 4 (4): 18 - 29
DOI: https://doi.org/10.56286/ntujet.v4i4

IRAQI Academic Scientific Journals

P-ISSN: 2788-9971 E-ISSN: 2788-998X
NTU Journal of Engineering and Technology
Available online at: https://journals.ntu.edu.iq/index.php/NTU-JET/index

Impact of Corrugation Surface and Nanofluid Flow on Hydrothermal Performance: A Review

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Article Informations

Received: 07-05- 2025,
Revised: 15-09-2025,
Accepted: 18-09-2025,
Published online: 28-12-2025.

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Key Words:
Corrugation surface,
nanofluid,
hydrothermal performance,
computational fluid dynamics.

A B S T R A C T

This article reviews several parts of previous studies, including both numerical and experimental investigations that examined the effects of heat transfer and pressure drop when using nanofluids or conventional fluids. The study presents design parameters, practical scales, and summarized results of earlier work in tabular form, accompanied by appropriate discussion. It also examines the influence of different types of nanoparticles(including metal oxides, nonmetals, and metals)on the basic thermodynamic and hydraulic behavior of working fluids, as well as the role of base fluids such as water and air. The review highlights that some research topics remain attractive and worth further exploration due to their simple design and high performance. In contrast, other topics are hindered by limitations, such as the challenges of applying complex geometries or the negative effects of increased pressure drop and nanoparticle agglomeration on channel walls, which can obstruct heat transfer. Overall, this review provides a foundation for more advanced studies on the performance of nanofluids in corrugated channel systems. These insights are valuable for guiding the design of compact and energy-efficient heat exchangers, with potential benefits in reducing energy consumption and environmental impact. Future research should focus on improving nanoparticle dispersion techniques, mitigating pressure drop penalties, and exploring hybrid nanofluids and innovative channel geometries to achieve even better hydrothermal performance.

1. Introduction

Due to the rising global energy demand, there has been a corresponding increase in pollution, specifically contributing to global warming [1]. Additionally, there is a need to decrease the operational costs of systems by reducing energy use. Researchers sought to maximize the efficiency of the systems. The heat transfer augmentation approach is one of the focal points of these studies. Over the past several decades, the utilization of this approach, particularly heat exchange equipment, has significantly diversified and expanded, resulting in the production of more efficient systems that conserve energy and reduce cost [2].

Various techniques have been utilized, including surface change, flow characteristics manipulation, and the incorporation of substances like nanoparticles. Maximizing the heat transmission ratio while minimizing the pressure lose is essential for creating highly efficient and compact heat exchangers. Developing more streamlined energy systems poses a substantial obstacle for academics and engineers [3,4]. The goal was to decrease energy usage to improve the system energy efficiency. This system will decrease heat exchanger mass, reduce size, and lower fabricating cost [5,6].

Three main methods for augmentation the heat transmission ratio are active, passive, and compound effect to flow control schemes The active flow control approach needs external power for heat transmission augmentation. Applications include oscillating or vibrating the flow, channel or pipe vibration, exposed to magnetic field, and other related process. This particular kind offers superior improvement in mixing the flow and heat transmission. Passive effect to flow control technology enhances heat transfer without requiring additional power input; however, it does result in more pressure loss due to geometric alterations. Passive flow may be achieved by several means, such as insert baffles, additives like nanoparticle, roughing surfaces, make vorticity in flow devices, corrugate surfaces, and coiled tubes or channel [7,8]. The compound flow control approach uses a mixture of two or more flow control technologies to improve the heat transmission ratio like changing surface configuration of channel or pipe with making vibration in flow [9].

Corrugation in channels and pipes greatly enhances heat transfer in many applications. The main objective of corrugation is to enhance heat transmission ratio by increasing the available surface area compared to a flat surface. Furthermore, corrugation greatly enhanced the transfer of heat by promoting flow mixing. This also resulted in the regeneration of the thermal boundary layer [10,11]. The researchers aimed to use these characteristics and optimize them by manipulating geometric parameters to get the most favorable outcomes. In addition, using corrugations inside channels with other techniques such as nanofluids, improve heat transmission ratio results in further improvements. In addition, using nanofluid in the corrugated channel helps decrease the incidence of stagnation in certain regions of the flow area [12].

The introduction of corrugation in channels and the addition of nanoparticles to the working fluid are considered effective techniques for enhancing heat transfer. Performance shows significant improvement when these two approaches are combined. In this study, and for clarity of explanation, the related review is classified into two categories: corrugated channels using conventional fluids as the working fluid, and corrugated channels using nanofluids. This classification allows for a clearer comparison of hydrothermal performance under different working conditions.

2. Effect of Corrugation Geometry

2.1 Numerical studies

Corrugated channels in literature are the first kind of channels used to augment the rate of heat transmission. The study [13] found that improving heat exchanger geometrical parameters improves heat transmission, which promotes thermal process efficiency and lowers operating costs. Hydrothermal performance of sinusoidal, trapezoidal, and straight pipes in heat exchanger at laminar flow of water and engine oil was investigated numerically across Re from1100 to2300 and 250 for water and engine oil receptively. They indicated that channel height (a) affected Nu more than the channel length (p). The research also found that the trapezoidal channel affected more than the sinusoidal and straight channels.

Using an individual corrugation configuration pattern. [14], specifically examine thermal efficiency of corrugated tubes by changing (a). The various forms of corrugations, including (outward arc, inward arc, outer arc-inward arc, and inward arc-outward arc) are studied to evaluate entropy generation and hydrothermal performance when subjected to a constant wall heat flux. They concluded that the configuration type (inward and outward arc) corrugations leads to enhanced in heat transmission for all the flow rates. However, this improvement in heat transmission ratio occurs with an increase in pressure drop.

Reference [15] investigated the evolution of heat transmission ratio and pressure drop inside a corrugated channel. Two plates with trapezoidal grooves and three different inclination angles 20°, 40°, and 60° were tested with the corrugated plates.

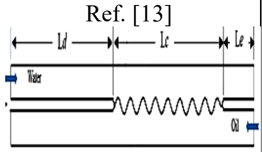
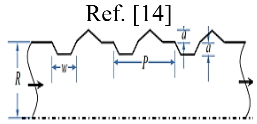
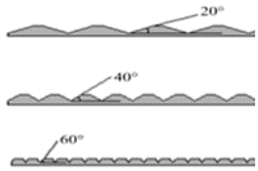
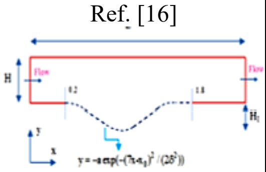
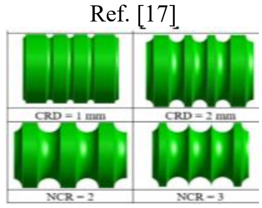
They investigated Re between 600 and 1400 and ran the model with a heat supply of 0.58 kW/m2. As a result, the average Nu for a corrugated channel can increase up to 4.5 times higher than flat channel. The most efficient option in terms of energy savings is a corrugated channel that has a 60° wave angle.

The numerical models of turbulent flows in a channel with waves were examined in [16] study. 2-dimensional, symmetrical channel under investigation is modeled across the Re from 10,000 to 80,000. This study has been evaluated seven methods for simulating turbulent flow in a corrugated channel: (k-σ SST, k-ϵ RNG, k-ϵ Realizable, k−ϵ Standard, k-ω Standard, Reynolds stress, and Spalart Allmaras). The results demonstrate that the best models for these geometries were found to be k-ω SST techniques and Reynolds and Spalart-Allmaras stress.

[17] studied the effect of various pauses on the corrugation process. They studied how combining secondary, spiral, and swirl flows impacts the pressure drop and heat transmission ratio. Because of the spiral flow, heat transmission ratio is greatly enhanced, and pressure drop is raised. According to the results, as the value of Re grows, the Nu tends to rise. An excellent Nu value indicates a more complex geometric design with more corrugations.

Table 1 presence the summary of previous studies.

Table 1. Summary of studies which conducted in channels that has corrugated groove.

parameters	remarks
Ref. [13]  Re= 1100-2300 T_{water}= 298 K T_{oil}= 350 K H=10mm a=0-5mm p=20-40mm L=200mm	-Counter flow between water and engine oil with three type of geometry surface (trapezoidal, sinusoidal, flat). -Nu is more significantly affected by the wave height rather than the wavelength. -The trapezoidal channel has a more pronounced influence.
Ref. [14]  q_w=50kw/m^2 T_{in}= 300 K Re=15000-37500 Water as working fluid L=100mm H=10mm p=5mm a=0.25mm	-Various forms of arc corrugations are used to evaluate the entropy generation and PEC. -Inward and outward arc corrugations improve heat transfer at all flow rates. -The arrangement with an outward and inward arc produces the least overall entropy at maximum Re.
Ref. [15]  q_w=580W/m^2 Re= 600-1400 θ= 20°, 40°, 60° Tin= 300 K Air as the working fluid H=12.5mm a=5mm L=323mm	-Examine varying inclination angles of the corrugation sections. -The average Nu for a corrugated channel can be up to 4.5 times higher than that of a smooth channel. -The most efficient option in terms of energy savings is a corrugated channel that has a 60° wave angle.
Ref. [16]  Re= 10000-80000 2-D symmetrical channel Water as working fluid P=3.68H	-Uses seven methods (k-σ SST, k-ϵ RN, k-ϵ Realizable, k−ϵ Standard, k-ω Standard, Reynolds stress, and Spalart-Allmaras). -The best models for these geometries were found to be k-ω SST, Reynolds and Spalart-Allmaras stress.
Ref. [17]  Re= 2000-5000 Tin= 313 K Water as working fluid L=1920mm D=11.08mm t=2mm PRA=60°, 80°, 330° NCR=2, 3, 4 CDR=1, 2, 3 mm.	-Studded impact of combining secondary, spiral, and swirl flows. -3-D corrugated pipe with different shapes. -The changes in vorticity become more apparent as the outer pipe moves closer to the center pipe. -As NCR rises, it is found that mixing and recirculation flow zones near the rings also increase, but the area around the rings remains untouched.

Reference [18] conducted research to examine how the hydrothermal performance of a Finned Microchannel in heat sink is affected by its shape and operating circumstances. Computational Fluid Dynamics (CFD) study evaluated four different forms of microfine (conical, pyramidal, cylindrical, and cubical). The findings indicated that Re was the most impact factor for the pyramid and conical. The most significant impacts on cylindrical shape were seen in the diameter of fins. In the end, the pyramidal fins demonstrated superior overall performance.

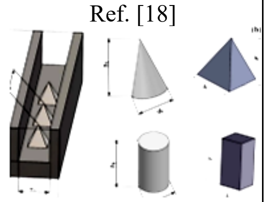
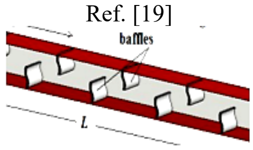
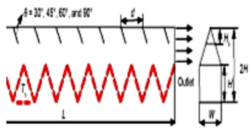
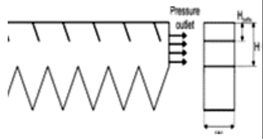
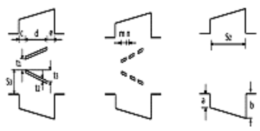
[19] used baffles to create corrugated geometry. This study investigates the impact of the baffle design, with a particular focus on the slop. The slop of the baffle is modified from 0o (a straight baffle) to 45o. Additionally three scenarios are examined, specifically: h/H = 0.4, 0.5, and 0.6. They concluded that PEC significantly enhanced up to 1.53 when the corrugation angle was raised to 45°, compared to the straight channel.

Karabulut [20] and Alnak [21], the studies focused on numerical investigating the impact of varying placement angles of baffles on heat transmission and pressure decrease in the top of the channel. The entrance temperature of the air utilized as the working fluid was 293 K. Height and apex angle of the baffle have been kept constant. The Re range under investigation is 1000-6000, while the baffle placing angles being considered are 30°, 45°, 60°, and 90°. The only difference between the two publications is in the configuration of the baffles. Karabulut used triangular baffles, while Alnak employed rectangular baffles. According to Nu viewpoint, it is shown that triangle baffles with a 60° angle are more effective than with a 90° angle. In rectangular baffles, the opposite phenomenon occurs. When comparing the findings based on pressure drop, it is seen that both triangular and rectangular baffles exhibit the maximum value at a 90o angle.

The work [22] measured the impact of pulsing flow on the hydrothermal performance of a corrugated channel equipped with V-shape baffles. The study examined three distinct flows, each with a different configuration (non-winglet, solid winglet, and perforated winglet). The results indicated that the configuration of the channel and winglet significantly influenced both heat transfer and flow properties. The pulsation parameters had a substantial role in enhancing heat transmission, particularly at high Re. Furthermore, they concluded that the presence of perforated winglets decreased the pressure losses if with solid winglet.

Table 2 presence the summary of the studies which has baffles in chnnels.

Table 2. Summary of the studies which has baffles in chnnels.

parameters	remarks
Ref. [18]  Re= 200-800 T_{in}=288 K q_w=100W/m^2 Water as working fluid L=30mm a=0.8mm	-Studying four different fin forms (conical, pyramidal, cylindrical, and cubical) shapes. -Conical and pyramidal forms were most affected by Re. -Pyramid fins had 5%, 10%, and 17% lower thermal resistance than conical, cylindrical, and cubical fins.
Ref. [19]  Re= 3-200 α =0-45° T_{in}=333 K T_w=268 K Water as working fluid. L=400mm a/H =0.4-0.6	-Studied the impact of the baffle design, with a particular focus on the wavy curve. -The total performance factor significantly enhanced when the corrugation angle was raised from 0° to 45°. -The design with a ratio of a/H = 0.5 was the optimal choice
Ref. [20]  Re=1000-6000 T_{in}=293 K T_{wall}=373 K Air as working fluid a=3.5355mm H=7.071mm L=70.71mm W=8.165mm	-Studied the impact of varying apex angles of triangular baffles on heat transmission and pressure drop. -At Re of 4000, an increasing in Nu by 8.2% for a baffle angle of 60° compared to 90° -At Re of 1000, the pressure drop in the channel with a 60° baffle angle is 39% less than in a 90°.
Ref. [21]  Re=1000-6000 T_{in}=293 K T_{wall}=373 K Air as working fluid a=3.5355mm H=7.071mm L=70.71mm W=8.165mm	-Studied the impact of varying apex angles of rectangular baffles on heat transmission and pressure drop. -At a Re of 6000, an increasing in Nu by 52.8% for a baffle angle of 90° compared to 60° -At Re of 1000, the pressure drop in the channel with a 60° baffle angle is 65.97% less than in a 90°.
Ref. [22]  T_{wall}=350 K T_{in}=293 K Re= 200-1000 A=0.5-1.5 St=2-8 Water as working fluid H=12mm S_2=18 mm S_3=5 mm b=5 mm c=3 mm d=8 mm e=7 mm t_1=2 mm t_2=0.3 mm t_3=3 mm m=2 mm n=1.2 mm	-Investigated the impact of pulsing flow on the hydrothermal performance of a corrugated channel equipped V-type winglets with three different configurations (non-winglet, solid winglet, and perforated winglet). -The configuration of the channel and winglet significantly influenced hydrothermal performance. -The pulsation had a substantial role in enhancing heat transfer, particularly at high Re. -The presence of perforated winglets decreased the friction.

Backward-Facing Step (BFS) Combined with Corrugated wall is also another demanded corrugation. [23] focused on the numerical investigation by combining BFS with various corrugated walls such as triangular, zigzag, and trapezoidal shape. The downstream wall was subjected to a uniform heat flux, while other walls were assumed as adiabatic surfaces. The study included some parameters like corrugation shape, height, and Re within the range of 5,000 to 20,000. The researchers found that the trapezoidal corrugation with a height of 4 mm showed the most effective enhancement in heat transmission.

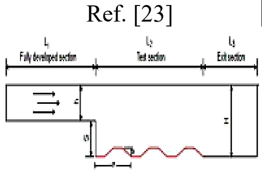
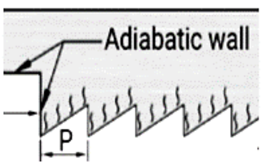
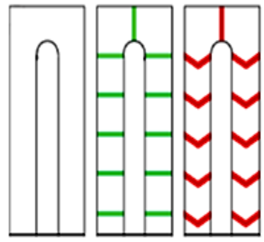
The research [24] conducted a numerical study of the heat transmission and turbulent flow via BFS that attaches to a corrugated wall using different triangle shapes The channel has a flat top surface, and triangle bottom surface after expended with different (p) at a fixed height (H) of 5 mm. A heat supplied was of 4 kW/m^2. Re was investigated from 5000 to 20000. As a result, heat transmission is enhanced on all surfaces, but the most significant performance occurs at Re = 5000and 10000.

2.2 Experimental studies

A study [25] proposed the impact of wavy shape ribs on vortex production and PEC in a rotating channel with rectangular cross section area. A novel wavy rib type is compared to rectangular ribs at Re 4000 to 12000. The study demonstrated that wavy shaped ribs exceeded rectangular cross section ribs in heat transmission performance (25% greater).

Table 3 presence the summary of studies which conducted BFS in channels that has corrugated groove.

Table 3. Summary of the studies for BFS and experimental setup.

parameters	remarks
Ref. [23]  Re= 5000-20000 q_w= 4 kW/m^2 T_{in}=300 K Water as working fluid H_{in}=10mm H_{out}=20mm a=1-5mm p=20mm L=200mm	-Studied the effect of BFS with different corrugated walls (zigzag, triangular, and trapezoidal). -The trapezoidal corrugation with a height of 4 mm and a diameter of 20 mm showed the most effective enhancement in heat transmission. -Nu was increased by up to 62% at Re of 5,000.
Ref. [24]  Re=5000-20000 q_w=4 kW/m^2 water as working fluid P=5-15mm a=5mm L=300 H_{in}=10mm H_{out}=20mm	-Studied the effect of BFS with different pitch length of corrugated walls. -The most significant increase in heat transfer occurs at Re = 5000and 10000 for the channel with a 10 mm pitch length. -In the channel with a 20 mm pitch length, the greatest PEC values are achieved at Re = 15000 and 20000
Ref. [25]  Re=4000-12000 T_w=473 K Air as working fluid W=600mm H=80mm L=500mm D_h=40mm	-Experimental study for vortex production and hydrothermal performance for wavy ribs in a rotating rectangular channel. -Wavy ribs performed 25% better in heat transfer than rectangular ones. -Wavy ribs reduce pressure drop and increase turbulence mixing if compared to rectangular ribs.

3. Effect of Corrugation Geometry with Nanofluid

Nanofluid represent a novel passive approach for enhancing heat transmission ratio that has attracted considerable interest from researchers over the last twenty years. This is because of its claimed high efficiency in a wide range of heat transmission applications [26, 27]. Dispersing solid nanoparticles in a base fluid may significantly improve thermal conductivity, resulting in increased thermal performance. However, this improvement comes at the cost of a small increase in pumping power [28, 29].

Nanofluid is classified into many categories based on the kinds of nanoparticles included. Nanoparticles may exist in metallic, nonmetallic, or hybrid forms, known as hybrid nanofluids. The transport characteristics of nanofluids are contingent upon the dispersion of various nanoparticles within the base fluid. The density, thermal conductivity, and specific heat of nanoparticles vary depending on their physical and chemical properties. Metallic nanoparticles, like Cu, Zn, Al, and others. Metallic oxide, including CuO, TiO_2, and ZnO, are classified as another type of nanoparticles. These nanofluids are mostly used for their exceptional thermal properties. Hybrid nanofluids consist of a mixture of both oxide and metallic nanofluids. Currently, there is a higher demand for carbon-based nanofluids and hybrid nanofluids because of their improved thermohydraulic performance. However, a significant disadvantage of using carbon-based nanofluids is that they raise the viscosity of the base fluids significantly. Fig. 1 is provided to illustrate the extensive categorization of nanoparticles [30, 31].

3.1. Numerical studies

Conventional fluids such as water might be regarded as poor thermal property because of their low thermal conductivity.

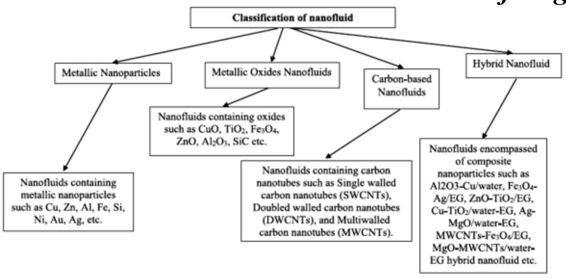


Fig.1. Extensive categorization of nanoparticles [30]

Consequently, to enhance this property, nanofluids are used as working fluid becuse it has effective thermal property material [32,33].

Using geometrical modifications, in conjunction with implementing high thermal conductivity nanofluid may significantly accelerate heat transmission. A numerical investigation conducted by [34] studied the effects of turbulent pulsing fluid flow, namely SWCNT/H_2O nanofluids, in a sinusoidal curved channel. The study focused on hydrothermal characteristics and entropy generation by using two different models (the homogeneous single-phase and the Lagrangian-Eulerian models). This simulation includes the variables of pulsation frequency, Re, and concentration ratio (Φ). The results indicated that the various friction factor and Φ play a significant role in enhancing PEC and reduce entropy generation in the wavy channel. Ultimately, the researchers suggested using SWCNT/H_2O at 0.03 of Φ in the channel gives superior heat transmission ratio and little frctional irreversibility.

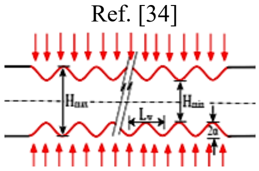
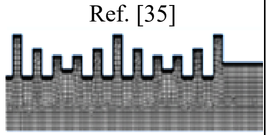
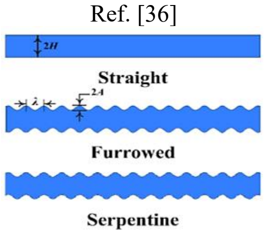
Another investigation [35] examines the effectiveness of nonuniform wall corrugations in enhancing heat transmission via a rectangular corrugated channel with convection heat transfer. The study compares three distinct types of nonuniform wall corrugations: gradually increasing (GIWC), gradually decreasing (GDWC), and periodic wall corrugation (PWC). These are then contrasted with uniform corrugation (UWC). The hybrid nanofluid used in this study combines GnP and MWCN mixed with pure water. The calculation is performed under heat supply circumstances of 2 kW/m^2 on the surface of the corrugated wall with the Re ranging from 500 to 2000. At Re 1000, the heat transmission ratio was increased by 15.61%, 18.70%, and 21.16% for GDWC, GIWC, and PWC respectively if compared to UWC.

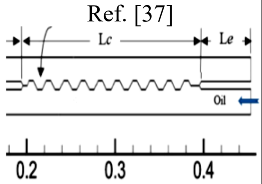
Reference [36] examines the turbulent hydrothermal efficiency and the rate of entropy generation of reduced-graphene oxide/cobalt oxide nanoparticles dispersed in water, flowing via straight, furrowed and serpentine wavy channels. The study investigated the impact of different Re, Φ, (a), and (p) on the hydrothermal and entropy generation ratio. The findings indicate that the average Nu, pressure drop, and entropy generation ratio resulting from viscous dissipation are greater in wavy channels if compared to straight one.

The work [37] aims to analyze the thermal characteristics of Al_2O_3/H_2O nanofluid in both square and sinusoidal channels. The evaluations were conducted at laminar flow with a constant heat supply to the walls. The study was concerned several factors, including particle concentration, particle diameter and Re. An important finding was that using nanofluid give significant improvements. In addition, the sinusoidal channel demonstrated the most efficient heat transmission and fluid flow characteristics at a Re of 800 and Φ of 5%, with PEC around 1.6. The researchers commented that instead of using corrugated channel, it is more advantageous and favorable to use tiny nanoparticle diameters and high values of both Φ and Re.

Table 4 presence the summary of previous studies which conducted in channels that has corrugated groove or baffles and use nanofluid as working fluid.

Table 4. Summary of previous studies that has corrugated groove or baffles and use nanofluid as working fluid.

parameters	remarks
Ref. [34]  Re=4000-7000 q_w=4553 W/m^2 θ=0°-180° Φ=0-0.03 SWCNT/H_2O nanofluid. p=28mm L=336mm a=3.5mm H_{min}/H_{max}=0.5	-Studied the impact of turbulent pulsating flow in a sinusoidal channel. Variables friction factor and Φ play a crucial role in enhancing the heat transfer and entropy generation in the wavy channel. -Using Φ = 0.03 of SWCNT/H_2O nanofluid in the channel, owing to its superior heat transfer ratio and little thermal irreversibility.
Ref. [35]  Re=500-2000 q_w=2000 kW/m^2 T_{in}=300K Φ=0.001-0.002 GnP-MWCN/H_2O nanofluid. L=36H a=0.05H-0.2H	-Compare three distinct types of nonuniform wall corrugations in tube. -Corrugation has the greatest average Nu among other alternatives but it increases in the pumping power compared to the others. -The hybrid nanofluid with Φ of 0.002, exhibited the greatest performance.
Ref. [36]  Re=5000-30000 q_w=5 kW/m^2 T_{in}=300K Φ=0-0.002 rGO-CO_3O_4/H_2O as working fluid.	-Examine the turbulent hydrothermal efficiency and the rate of entropy generation of hybrid nanofluid flowing through straight, serpentine, and furrowed wavy channels. -The average Nu, pressure drop, and the viscous entropy generation rate, are greater in wavy channels compared to straight channels.

H=0.1m a=0.2-0.6 p=0.7-1.4 L=2m	-These values decrease as pitch increases.
Ref. [37]  Re=200-800 T_{in}=298K q_w=5 kW/m^2 Φ=0-0.05 Al_2O_3/H_2O nanofluid. p=2H a=0.02H L=20H	-Analyze entropy generation and hydrothermal performance of nanofluid flow in both sinusoidal and square channels. -The sinusoidal channel has the best PEC value about 1.6. -Total entropy generation falls by 28.39% and 22.12% for sinusoidal and square respectively with increasing Φ.

Some researchers have studied the hydrothermal characteristics of corrugated circular tubes using nanofluid as the working fluid. [38] performed analytical study using CuO/H_2O nanofluid in a circular pipe with varying angle of baffles. The duct surfaces containing baffles are assumed at a temperature of 340 K. The research examines the impact of varying Re, volume concentration and baffle angles on thermal enhancement factor and friction factor. The numerical analysis demonstrates that the presence of baffles and the use of nanofluid flow substantially improve thermal performance. The baffles angle at 90º yields the most significant enhancement in thermal ratio and friction factor. However, baffle at angle 150º provides the best PEC.

Reference [39] examines the rate of entropy is generated in a nanofluid consisting of (Fe_3O_4/H_2O) as it flows through corrugated pipes of various profiles such as (triangular, circular, and trapezoidal). The simulation uses the multi-phase and the k-ω turbulent model. An investigation was conducted to analyze the impact of Re and volume fraction on the rates of viscous entropy generation and thermal entropy generation. The researchers found that trapezoidal corrugated pipes exhibit superior PEC but have the poorest hydraulic performance. The thermal entropy generation rate is mainly influenced by the mean temperature gradient instead of the turbulent temperature gradient.

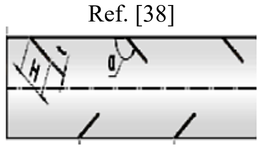
The research [40] examines the effect of AlN/water nanofluid to heat transmission ratio in laminar flow with four type of channels (flat, triangular, BFS, and trapezoidal). Numerical analysis examined the impact of Re between100 to 1500 and nanoparticle volume fraction on heat transmission ratio and fluid flow. As a result, compared to base fluids, nanofluids have higher thermal convection ratio as nanoparticle volume fractions and Re grow.

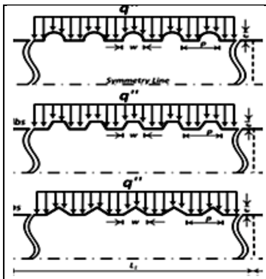
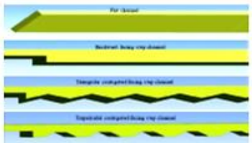
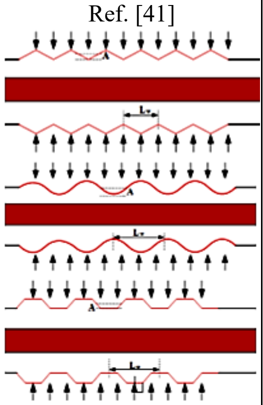
Reference [41] conduct numerical analysis to investigate the thermohydraulic properties of forced convection in a corrugated channel which has several profiles, including (triangular, sinusoidal, and trapezoidal) shapes. Additionally, a single layer of porous foam made of aluminum is integrated into the channels core. The results were obtained by varying the Re and Φ of nanoparticles while keeping the Darcy number constant at 10^{-6}. the researchers showed that orrugations and baffles are effective passive technic by disturbing thermal and hydrodynamic boundary layers.

Table 5 presence the summary of previous studies which conducted in circular pipe or channels with porous inserted.

An investigation was conducted on the heat transmission properties of Al_2O_3/H_2O nanofluid inside a corrugated channel, including a flat blade [42]. The combined impacts of the blade's scenario (oscillating or stationary) and the channel walls shape (corrugated or straight) on thermohydraulic performance. The simulations were carried out at various Re, Φ, and diameters. The findings demonstrated that, while operating at high Re, the use of a stationary/oscillating blade had a substantial impact on the thermal efficiency of the corrugated channel, exceeding of the straight channel. The total Nu rose as Φ increased and the nanoparticle diameter decreased in both type channels, regardless of the presence or absence of a fixed or oscillating blade. An analysis of PEC revealed that a significant Re could be identified when both stationary and oscillating blades were present. This Reynolds number corresponds to the highest and lowest values of the PEC, respectively. Consequently, by turning on the oscillating blade when the Re are high and turning it off when the Re are low, there is a potential for a substantial enhancement in PEC. Increasing the volume percentage made PEC more sensitive to changes in nanoparticle diameter, even if this factor was less important.

Table 5. the summary of previous studies which conducted in circular pipe or channels with porous inserted.

parameters	remarks
Ref. [38]  Re=200-1000 T_w=340K T_{in}=293K α=30º-150º Φ=0.01-0.03 d_p=20nm-50nm CuO/H_2O as working fluid L=635mm D_h=19mm p=38mm	-Examine the impact of baffle angles on nanofluid flow and heat transmission in a circular duct Nu and friction factors positively correlate with Re and Φ. -At 90º baffle angle produces the highest thermal enhancement and relative friction factors. -At 150º baffle angle, yields the highest PEC value.
Ref. [39]	-Examines the rate of entropy is produced in a nanofluid through corrugated pipes at various profiles (circular,

 Re=5000-30000 T_{in}=300K Φ=0-0.03 Fe_3O_4/H_2O as working fluid L=178mm D_h=20mm (a/D_h)=0.03826 (p/D_h)=0.6	triangular, and trapezoidal). -Trapezoidal corrugated pipes exhibit superior heat transfer performance. -The presence of corrugation leads to an increase in the rate of viscous entropy generation while reducing the rate of thermal entropy generation.
Ref. [40]  Re=100-1500 T_{in}=298K Φ=0.01-0.04 AlN/H_2O nanofluid. H=50mm a=0-4mm p=20-100mm	-Examines the effect of nanofluid to heat transfer in laminar flow with four type of channels: (flat, BFS, triangular, trapezoidal) -At high Φ of 0.04, the four channel designs increased heat transmission by 30% if compared with the trapezoidal shape with pure water.
Ref. [41]  Re=5-500 Φ=0-0.05 Da=10^{-6} CuO/H_2O nanofluid.	-Studied thermohydraulic effects of corrugated channel which has several corrugated profiles (triangular, sinusoidal, trapezoidal) shapes with single layer of porous foam made of aluminum. -Installing a corrugated wall enhances the mixing capacity between the hot and cold fluid. -The trapezoidal corrugated channel exhibits superior enhancement in heat transfer.

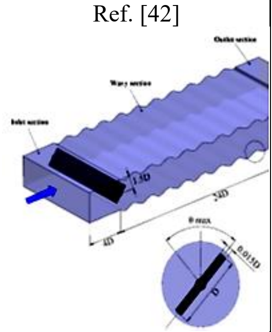
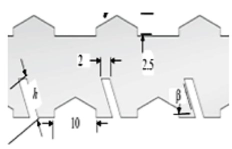
Reference [43] A numerical investigation was conducted to analyze the hydrothermal performance of a ribbed corrugated channel. The study included various Re, namely 5,000 to 25,000 of nanofluid consisting of $CuO\text{-}MgO/H_2O$. Researches have shown that ribs with a 90° attack angle are more desirable than ribs with a smaller attack angle for achieving the best hydrothermal performance in a channel. A hybrid nanofluid flowing via a corrugated channel outperforms the base fluid in all scenarios. The channel being studied had the highest PEC of 2.22 at angle of 90°.

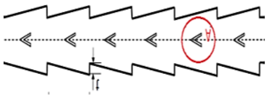
Another work [44] conducted a numerical analysis to investigate the effects of central winglets and the use of Al_2O_3/H_2O nanofluid on the PEC inside a zigzag channel. The top and bottom zigzag surfaces temperature is maintained at 350 K. The findings indicate that using nanofluid and winglets significantly improves heat transmission, although with a modest rise in the friction factor. PEC reaches its maximum value of roughly 2.12 at a Re of 400 and nanoparticle volume fraction of 0.05.

Table 6 presence the summary of previous studies which has corrugated grooves with baffles.

A novel study proposes a new approach about thermoelectric generator module. The aim of the research is to improve the performance of it which positioned between two channels that transport hot and cold fluid streams [45]. The technique involves using both types of hybrid nanofluid and surface corrugation. The finite element technique solves the coupled field equations in three dimensions. The study investigates the effects of Re, groove number, amplitude (ranging from H/8 to H/1.75), and type (circular and rectangular) of the groove, as well as the volume fraction of the hybrid nanofluid on the characteristics of fluid flow, heat transmission ratio, and power generation. The results indicated that the thermoelectric power module increases with high Re, Φ of the hybrid nanoparticles, height, and number of waves in both circular and rectangular corrugation types. The amplitude has a more significant influence on the produced power than the number of waves in the groove.

Table 6. Summary of studies which has corrugated grooves with baffles.

parameters	remarks
Ref. [42]  Re=25-250 T_{in}=293K Φ=0-0.04 d_p=25-100nm Al_2O_3/H_2O as working fluid	-Investigate the combined impacts of the blade's and the channel walls on thermal-hydraulic performance. -Nu increased as Φ increased and nanoparticle diameter decreased in both straight and corrugated channels. -Turning on the oscillating blade when Re is high and off when Re is low may significantly improve PEC.
Ref. [43]  Re=5000-25000 T_{in}=300K T_w=365K $CuO\text{-}MgO/H_2O$ as working fluid L=200mm	-Studied hydrothermal performance for corrugated channel by considering the combined effect of inclined ribs and a nanofluid. -Ribs with a 90° are more desirable for achieving the best thermal performance in a channel but cause pressure drop.

H=10mm a=2.5mm w=50mm	-The channel had the highest PEC of 2.22 at an angle of 90°.
Ref. [44]  Re=200-1200 T_w=350K T_{in}=293K Φ=0.01-0.05 Al_2O_3/H_2O as working fluid H=19mm L=190mm p=28.5mm a=3.8mm	-Studied the effects of central winglets and the use of nanofluid on the PEC inside a zigzag channel. -Using nanofluid and winglets significantly improves heat transfer, with a modest increase in the friction factor. -PEC increases as the velocity and Φ increase. -PEC reaches its maximum value of roughly 2.12 at a Re of 400 and Φ of 0.05.

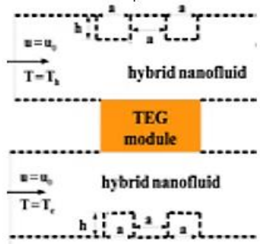
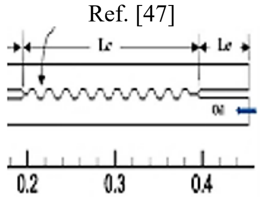
3.2. Experimental studies

A study was conducted experimentally to examine the impact of together turbulent flow with corrugated geometry on the hydrothermal performance [46]. Three different forms of the channels, namely (semicircular, trapezoidal, and a straight channel) were manufactured and subjected to testing using Al_2O_3/H_2O nanofluids. Al_2O_3 nanoparticles are successfully synthesized in water with two different Φ of 0.01 and 0.02. The experimental results indicate that the use of trapezoidal grooves improves PEC by 2.22 times when compared with straight one. Using corrugated groove with 0.02 volume fraction of nanofluid resulted in an approximately 7.9-8.3% increase in the heat transmission ratio.

A numerical and experimental analysis of the hydrothermal efficiency of a trapezoidal and straight shaped with counter flow heat exchanger were performed [47]. The analysis focused on the laminar flow of SiO_2/H_2O nanofluid and engine oil, covering Re ranging from 1100 to 2300 and 0.250 for the nanofluid and engine oil respectively. They concluded that using corrugated surfaces in counter flow heat exchangers with nanofluid can enhance heat transmission ratio, leading to increased efficiency and reduced operating costs.

Table 7 presence the summary of previous studies which conducted in channels that has thermoelectric generator and other experimental works.

Table 7. Summary of studies which conducted in corrugated channels that has thermoelectric generator and other experimental works.

parameters	remarks
Ref. [45]  Re=250-1000 Pr=6.9 T_{cold}=303K Φ=0-0.02 Ag-MgO/H_2O nanofluid No_{corr} =1-8 a=(H/8)-(H/1.75) L=22.2H w=4.81H	-Improve the performance of a thermoelectric generator module positioned between corrugated channels and using hybrid nanofluid. -Thermoelectric module power rises with increasing of Re, Φ, amplitude, and number of waves in both rectangular and circular corrugation. -Power rises by 10.95% at Re 250 and 7.50% at Re 1000, with Φ of 0.02. -Power is more affected by corrugation height than wave length.
Ref. [46]  Re=10000-30000 q_w=10kW/m^2 T_{in}=300K Φ=0.01-0.02 d_p=20nm Al_2O_3/H_2O nanofluid. H=10mm w=50mm p=15mm a=2.5mm L=200mm	-Experimental study to examine the impact of together corrugated walls and turbulent nanofluid flow on the hydrothermal performance. -The use of trapezoidal grooves enhances heat transfer efficiency by 63.59%, increases pressure drop by 1.37 times, and improves PEC by 2.22 times. -Increase Φ of Al_2O_3 leads to an enhancement in heat transfer owing to the corresponding rise in thermal conductivity.
Ref. [47]  Re=1100-2300 Φ=0-0.04 d_p=20nm SiO_2/H_2O and engine oil as working fluid H=10mm w=50mm p=20-40mm a=0-4mm L=200mm	-Experimental study to analysis the thermal and hydraulic efficiency of a trapezoidal and straight counter flow heat exchanger. -The use of SiO_2/water nanofluid has led to a substantial enhancement in heat transfer across all Re. -At a Re of 2300, the numerical and experimental works show an error deviation of 0.0512% and 0.0325% for pressure drop, respectively, and 0.0102% and 0.0208% for Nu respectively.

4. Conclusion

A comprehensive review was conducted on studies related to the use of modern cooling systems in thermal designs to improve performance and enhance heat transfer characteristics. The influence of several key parameters on heat transfer rates and pressure drop capabilities was identified. These parameters include nanoparticle size, type, shape, loading, passive treatment methods, and mass flow rate. The main findings can be summarized as follows:

- Increasing Re improves the thermal PEC and reduces overall entropy generation.
- Among different corrugated channel shapes, trapezoidal configurations provide the most significant heat transfer improvement, followed by sinusoidal and triangular forms. All corrugated designs outperform straight channels.
- Plate fins and ribs in microchannels show higher heat transfer and lower pressure drop compared to plate fins alone, across all configurations.
- Corrugation angle, height, inclination, and channel height play a critical role in optimizing heat transfer and pressure drop.
- The best heat transfer performance with baffles occurs at angles of 60° and 120°.
- Corrugation height (a) has a greater effect on heat transfer and friction factor than corrugation length (p), especially at higher Re.
- Sharp corrugations generally provide higher heat transfer but also cause higher pressure drop.
- Corrugations enhance heat transfer by disturbing the boundary layer and promoting fluid mixing.
- V-shaped baffles (winglets) at 45° deliver better PEC compared to other angles. Furthermore, perforated winglets reduce the friction factor.
- Under pulsating flow conditions, an optimal Re exists at which PEC reaches its maximum.
- The rise in the Re enhances PEC, reducing total entropy generation.
- The symmetrical configuration of the corrugations resulted in the most efficient heat transmission compared to the zigzag design.
- The heat transmission ratio increases when the Φ of nanoparticles is raised, reaching a maximum at a certain level known as the optimal volumetric concentration of the nanofluid. In addition, it raises the viscosity and friction factor, resulting in a penalty in pumping power.
- The temperature at which nanofluids operate is crucial for the efficiency of heat exchangers and the enhancement of heat transmission ratio.
- Including dimple ribs, insert baffles, or corrugated surfaces in the channel is more effective than adding nanoparticles. Additionally, combining dimple ribs, baffles, or corrugated surfaces with nanofluids further increases the heat transmission ratio

5. Recommendations

1. Researchers thoroughly studied the passive technics. Further consideration should be given to active techniques or the combination of passive and active methods to address the existing gap.
2. The researchers examined the corrugated channels flow behavior and heat transfer properties. However, experimental relationships must be established to accurately determine the heat transmission ratio and pressure losses, which are essential for assessing thermal efficiency. To assist heat exchanger designers and producers in their work, academics must devote more effort to providing correlations that may be readily used.
3. The capabilities of 2-D channel in heat transmission have been thoroughly examined. However, further research efforts are required to investigate 3-D channel geometries especially at complex geometries.
4. Most studies demonstrated favorable thermal characteristics when using nanofluid, which improved heat transmission ratio, reduced exergy destruction and decreased entropy generation compared to base fluids. However, the nanofluids developed for industrial applications necessitate high concentrations and kilograms of nanoparticles, which cannot be economically justified.
5. To comprehensively evaluate the performance of nanofluids in corrugated channels, it is essential to carefully take in to account the potential pollution and toxicity effects of the nanoparticles on both the environment and human health. Additional factors like the cost, their impact on pressure drop, and the systems overall energy efficiency should also be considered.

In light of the reviewed literature, future research should also explore hybrid nanofluids and advanced corrugation geometries to further optimize hydrothermal performance. Addressing these aspects will provide a clearer path toward the practical deployment of compact and energy-efficient heat exchangers in industrial applications.

Funding
This work funded in part by the Northern Technical University (3461 in 2022/9/11).

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