ENHANCEMENT OF HEAT TRANSFER STRATEGIES IN DOUBLE PIPE HEAT EXCHANGER: A REVIEW

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ABSTRACT

Double pipe heat exchangers (DPHEs) are widely used in various industries due to their simple design and high heat transfer efficiency. This review paper comprehensively examines methods to enhance heat transfer performance in DPHEs, categorizing them into active, passive, and compound methods. Active methods explored include rotating the inner tube, while passive methods cover twisted tapes, finned surfaces, wire coils, and nanofluids. Each method is analyzed for its impact on heat transfer rate, pressure drop, and overall thermal performance. The novelty of this paper lies in its detailed comparative analysis of these methods, providing insights into the optimal design and operating conditions for maximizing thermal-hydraulic performance. The review highlights that while methods like using nanofluids and twisted tapes significantly improve heat transfer, they also increase pressure drops, necessitating a careful balance to optimize efficiency. These findings serve as a valuable resource for researchers and engineers developing efficient DPHE systems.

Keywords: Heat exchangers, Thermal processes, Double pipe heat exchangers, Fins, Nanofluids.

ABBREVIATIONS AND SYMBOLS

f:	Friction factor
h:	heat transfer coefficient, W/(m^2 K)
h_n:	helical number
m:	mass flow rate (kg/s)
q:	Rate of heat transfer (W)
u:	rotation angle
A:	Heat transfer area (m2)
ANN:	Artificial neural networks
CFD:	Computational fluid dynamics
D:	Diameter of the tube (m)
DG-FEM:	Discontinuous Galerkin Finite Element Method

DPHE:	Double pipe heat exchanger
FEM:	Finite Element Method
GRA	Grey relational analysis
H:	Height (m)
LF:	Longitudinal fins
LR:	Long radius
NTU:	Number of transfer units
RE2b	Specific range of Reynolds number
Nu:	Nusselt number
PCM:	Phase Change Material
Re:	Reynolds number
SLF:	Split longitudinal fins
θ:	Temperature difference
ε:	effectiveness
Subscripts	
c	cold fluid
h	hot fluid
i	inner tube
o	outer tube

INTRODUCTION

Double pipe heat exchangers (DPHEs) have emerged as crucial components in various industrial applications, including power generation, chemical processing, refrigeration systems, and heating, ventilation, and air conditioning (HVAC) systems. Their simple and compact design, coupled with high heat transfer efficiency, has made them an attractive choice for processes involving heat transfer between two fluids at different temperatures. Continuous efforts have been directed towards enhancing the heat transfer performance of DPHEs to meet the ever-increasing demand for energy-efficient and cost-effective systems.

The heat transfer rate in a DPHE is primarily governed by the flow conditions, geometrical configurations, and thermo-physical properties of the working fluids. Traditionally, increasing the heat transfer surface area or inducing turbulence in the flow has been employed to augment the heat transfer rate. However, these methods often result in a trade-off between enhanced heat transfer and increased pressure drop, leading to higher pumping power requirements and operational costs.

Over the years, researchers have explored various techniques to overcome this trade-off and optimize the thermal-hydraulic performance of DPHEs. These techniques can be broadly classified into three categories: active methods, passive methods, and compound methods. Active methods involve the application of external power sources, such as mechanical aids or surface vibrations, to promote fluid mixing and disrupt the boundary layer. Passive methods, on the other hand, rely on geometrical modifications or the inclusion of inserts within the heat exchanger to induce swirl or turbulence in the flow. Compound methods combine active and passive techniques to leverage their synergistic effects, potentially achieving higher heat transfer rates while minimizing the associated pressure drop penalties.

Additionally, the advent of nanofluids has opened new avenues for enhancing the thermal conductivity of the working fluids, further improving the heat transfer performance of DPHEs. For example, studies by (Reddy & Vasudeva Rao, 2014) and (Saeedan et al., 2016) demonstrated significant improvements in heat transfer coefficients with the use of nanofluids, though these benefits often come with increased pressure drops.

This review paper aims to provide a comprehensive overview of the various methods employed to enhance heat transfer in DPHEs. It critically analyzes findings from experimental, numerical, and analytical studies, highlighting the advantages and limitations of each technique. The review also sheds light on the trade-offs between heat transfer enhancement and pressure drop, emphasizing the importance of optimizing the thermal-hydraulic performance for practical applications. By consolidating the current state of knowledge, this review serves as a valuable resource for researchers and engineers working on the development and enhancement of efficient double pipe heat exchanger (DPHE) systems.

AN OVERVIEW OF DOUBLE PIPE HEAT EXCHANGERS

The inception of the double-pipe heat exchanger can be traced back to a pivotal moment in the chemical industry, driven by the imperative to enhance productivity. In Figure (1), a simple schematic of a double pipe heat exchanger with bare pipes and counter-current flow.

One of the studies marking the early stage of developing the Double pipe heat exchanger is the one done by (Mozley, 1956) who analyzed the dynamic characteristics of concentric tube arrangements in a heat exchanger using mathematical equations and simple models. The study compared physical and analogue systems, focusing on higher frequency responses. It aimed to replace various other heat exchanger types and provide statistical data for designing efficient double-pipe heat exchangers DPHEs.

In the same period, an investigation of a heat exchanger was done by (Cohen and Johnson, 1956) using an experimental setup operated with steam to enhance capabilities, the response and frequency response of the heat exchanger were evaluated, with experimental data closely matching mathematical calculations.

A study for determining the required area for a heat transfer process is done by (Sullivan et al., 1961) by considering bulk temperature for inner and outer tube walls. They derived a correlation for gas heating and vapor condensation.

(Prasad, 1987) emphasized the importance of heat removal for efficient heat transfer equipment. He proposed transferring heat from inner to outer sections or vice versa, calculating accessibility using the NTU method over adiabatic conditions. Additionally, he developed a mathematical model for computing heat transfer equations in parallel and counter-flow configurations.

(Hsieh et al., 1987) conducted research to enhance heat transfer by increasing surface area and inducing turbulence in flow. They focused on validating heat improvement using helical tubes with roughened inner boundaries. The study varied Reynolds numbers from 3500 to 30000 to maintain turbulent flow, with (D_o/D_i) ratios varying from 2.68 to 5.1. A correlation is obtained between

Nusselt number and diameter ratio as follows:

$$Nu = 3.97\,(Re)^{0.554}\,(D_o/D_i)^{-0.72} \tag{1}$$

(Lachi et al., 1997) conducted experiments on transient states, employing the energy balance equation to determine the time constant. Comparing actual experimentation with hypothetical cases, they found a 10% increase in heat transfer for changing flow rates. Moreover, heat transfer showed a rapid increase with higher flow rates.

(Aicher et al., 1998) investigated a smaller heat exchanger with cross-flow. They studied counter flow in the nozzle section of a DPHE, finding it significantly impacts heat transfer and pressure drop. The effect is more pronounced in smaller heat exchangers with low ratios of free cross-sectional areas. They give experimental correlations to expect the transfer rates of the heat in turbulent flow.

(Ma et al., 2016) investigated the effects of supercritical carbon dioxide (SCO_2) in a DPHE, focusing on pressure, mass flux, and buoyancy force on the SCO_2-side. Increased gas-side pressure notably decreased overall and gas-side heat transfer rates. The water-side flow rate was found to be crucial for heat transfer compared to the gas-side. They proposed a mathematical correlation, utilizing Genetic Algorithm, to predict heat transfer rates.

Furthermore, (Templeton et al., 2016) investigated solar energy storage using DPHEs, employing numerical simulations with the finite volume method. The study focused on northern climates like Canada. The study noticed that the model accurately simulated variations in temperature during both injection and extraction situations, showcasing the potential of DPHEs in solar applications.

(Abdelmessih et al., 1999) explored the combined effect of various convection conditions, focusing on the U-bend with maximum achievable flow velocity. The study explored forced convection, natural convection, and variable heat flux across different sections of the U-bend.

(Suryanarayan et al., 1994) have devised various fin configurations to assess pumping power, with fins affixed to the outer surface of the outer pipe. They established a correlation between Nusselt number and Reynolds number to enhance heat transfer efficiency for both smooth and finned pipe arrangements

$$Nu(s) = 0.021\,(Re)^{0.793} \tag{2}$$

$$Nu(f) = 0.5\,(Re)^{0.64} \tag{3}$$

(Sheikhzadeh et al., 2002) conducted experiments to evaluate the thermal performance of a double-pipe heat exchanger and determine specific heat transfer characteristics. They found that the heat transfer coefficient on the outer tube side was smaller than that on the inner tube side by factors of 1.5 and 3.4 for counter-flow and parallel-flow configurations of the fluid, respectively.

(Maré et al., 2008) studied mixed heat transfer with backflow in concentric DPHEs through numerical and experimental approaches. Water, flowing in a laminar regime, served as the working fluid. They found that a high flow volume in the annulus resulted in a constant temperature boundary condition in the inner tube. Backflow was evident in both the inner tube and annulus, with a notable increase observed at low flow rates and when the Richardson number reached unity. Additionally, the Richardson number is defined as follows:

$$R_i = \frac{buoyancy\ term}{flow\ gradient\ term} = \frac{g\beta L(T - T_{ref})}{V^2} \tag{4}$$

where β is the factor of thermal expansion.

DPHEs have seen increasing application in solar and geothermal contexts. (Templeton et al., 2016) utilized numerical methods, specifically the finite volume technique, to examine solar energy storage with a DPHE, focusing on climates akin to Canada. Their simulation effectively replicated transient temperature shifts during injection and extraction processes.

HEAT TRANSFER IMPROVEMENT METHODS

This review delves into strategies for improving heat transfer through alterations in physical properties and diverse techniques. It classifies these strategies into three methods which are active, passive and compound. Active methods, though more energy-demanding encompass practices like jet impingement and mechanical adjustments. Passive methods involve integrating additional geometries like turbulators and roughened surfaces. Compound methods merge active and passive approaches for heightened efficiency, drawing on various studies to advance heat transfer methodologies.

Active methods

Active methods for enhancing heat transfer in double pipe heat exchangers (DPHEs) involve the application of external power sources to promote fluid mixing and disrupt boundary layers. These methods, while effective, often require additional energy input.

1. Rotating Inner Tube: (El-Maghlany et al., 2012) studied the effect of a rotating inner tube in a DPHE. They found that increasing the rotation speed improved the heat transfer rate and NTU (Number of Transfer Units), but also raised the pressure drop and friction factor, which could lead to higher operational costs. The rotation induces secondary flows that enhance mixing and disrupt thermal boundary layers, leading to better heat transfer.

2. Mechanical Vibration: (Heeraman et al., 2022) applying mechanical vibrations to the heat exchanger surfaces can enhance heat transfer. Studies have shown that vibrations can induce pulsating flow, which improves fluid mixing and disrupts the thermal boundary layer. However, the energy cost associated with generating vibrations must be considered.

3. Surface Vibrations: Surface vibrations can also be used to enhance heat transfer. (Zhang et al., 2012) demonstrated that using rotor-assembled strands in DPHEs increased the Nusselt number by 71.5–123.1%, significantly enhancing heat transfer. However, the friction factor also increased by 37.4–74.8%, indicating higher pressure drops.

4. Jet Impingement: (Iqbal et al., 2015) studied jet impingement involves directing high-velocity fluid jets onto heat exchanger surfaces. This method enhances heat transfer by disrupting boundary layers and promoting turbulent mixing. While effective, it requires precise control of jet parameters and additional pumping power.

5. Ultrasonic Vibrations: (Gnanavel et al., 2020) studied ultrasonic vibrations have been used to enhance heat transfer in DPHEs. These high-frequency vibrations induce cavitation and micro-streaming effects, significantly improving heat transfer rates. However, the equipment for generating ultrasonic vibrations can be costly and complex to maintain.

6. Magnetic Field Application: Applying a magnetic field to the heat exchanger can enhance heat transfer, especially when working with magnetic fluids. This method promotes better fluid mixing and disrupts the boundary layer. (Iqbal et al., 2015) explored this method and found significant improvements in heat transfer, though the setup and operational costs are higher due to the need for magnetic field generation equipment.

Passive method

Passive methods for heat transfer improvement involve surface or geometrical changes as well as the use of various inserts, all without the need for external forces. These modifications and inserts are designed to optimize heat transfer efficiency within the system.

Using of twisted tape

(Naphon, 2006) conducted experimental research on a horizontal DPHE, comparing performance with and without twisted tape inserts. The inserts, made of 1-mm-thick aluminum, were tested with hot water flowing in the inner tube and cold water in the annulus. Results demonstrated a notable effect of twisted tape inserts on heat transfer and pressure drop within the heat exchanger. Correlations were derived to predict heat transfer rate and pressure drop effectively, providing valuable insights for design and optimization purposes as shown in figure 2.

(Yadav, 2009) explored the impact of half-length twisted tapes within the inner tube of a double pipe U-bend heat exchanger (DPHE) on heat transfer and pressure drop. Compared to a smooth tube, the twisted tapes led to a 40% increase in heat transfer. However, the performance evaluation criterion of the smooth tube was found to be 1.3–1.5 times higher than that of the modified heat exchanger. This study highlights the limited investigation of twisted tape inserts in DPHEs as shown in figure 3.

(Khalaf and Falih, 2018) presents a comprehensive study on enhancing heat transfer in double pipe heat exchangers using twisted tape inserts as a passive method. The use of twisted tape is a well-known technique to improve the thermal performance of heat exchangers by creating turbulence, which increases the heat transfer coefficient. This study contributes to the field by providing experimental data and numerical analysis through ANN, offering insights into the effectiveness of twisted tapes in various configurations and flow conditions. The findings suggest that twisted tapes can significantly enhance heat transfer rates, making them a valuable addition to double pipe heat exchanger design for improved efficiency.

(Sridharan, 2022) used grey relational analysis (GRA) to optimize the efficiency and cold-water outlet temperature (t_2) of a heat exchanger system. The research considered factores like the mass flow rate of the cold fluid (m_c), the temperature of cold-water intake (t_1), the mass flow rate of the hot fluid, and the temperature of hot water inlet (T_1). The GRA strategy potentially increased the efficiency of the counter flow twin pipe heat exchanger by 12.06%.

(Chavan et al., 2023) achieved a study to maximize the heat transfer rate by monitoring the mass flow rates of two fluids. They placed washers between the outer and inner pipes to delay the cold fluid and accelerate heat transfer. Heat exchangers are used in power plants, the chemical and petrochemical industry, oil refining, sewage treatment, and heating and cooling systems. They are most commonly found in internal combustion engines, where they cool the engine coolant and heat the incoming air.

Application of Nanofluids in Double Pipe Heat Exchangers

Nanofluids, which are fluids containing nanometer-sized particles, have been shown to significantly enhance the thermal properties of base fluids, leading to improved heat transfer performance in DPHEs. There are various types of nanofluids, including metal oxides (e.g., Al_2O3, TiO_2), metals (e.g., Cu, Ag), and carbon-based nanomaterials (e.g., CNTs, graphene), have been studied for their thermal performance in DPHEs. The choice of nanoparticles, their concentration, and the base fluid are critical factors influencing the heat transfer enhancement.

The mechanisms by which nanofluids enhance heat transfer include increased thermal conductivity, enhanced convective heat transfer due to nanoparticle-induced micro-convection, and improved thermo-physical properties such as density and viscosity.

Several experimental and numerical studies have demonstrated the effectiveness of nanofluids in DPHEs. (Reddy and Rao, 2014) conducted experimental research on the heat transfer coefficient and friction factor of T_iO_2 nanofluid in a twin pipe heat exchanger, with and without helical coil inserts. The study found that the friction and heat transfer coefficient increased by 10.73% and 8.73% respectively for a nanofluid volume concentration of 0.02%, and further increased when a helical coil insert was used. The results were compared with existing literature, and generalized correlations for the Nusselt number and friction factor were provided. The inaccuracy was from 10 to 15%.

(Saeedan et al., 2016) conducted a numerical analysis on the thermal performance of a helically baffled heat exchanger with a 3D filtered tube using nanofluids. They considered Cu, CuO, and CNT nanoparticle nanofluids at various concentrations. The study found that increasing the volume concentration and Reynolds number intensified heat transfer and reduced pressure. The Nusselt number increased for CuO/water and Cu/water nanofluids but decreased for CNT/water with increasing volume concentration. A neural network was used to model the Nusselt number and pressure gradient, providing accurate predictions.

(MageshBabu et al., 2017) studied the thermal behavior, heat transfer rate, and friction factor of Al_2O_3/DI water nanofluids in a micro finned tube with helical inserts. The study compared these factors with a plain tube, finding the micro finned tubes with inserts to be superior. An empirical relationship between the Nusselt number (Nu) and friction factor (f) was established for straight twisted tubes and left-right combinations. The study found that a micro fin tube with an LR twist and a nanofluid concentration of 0.2% provided the best thermal performance.

(Baba et al., 2018) conducted a study to improve heat transmission in heat exchangers using Fe_3O_4-water nanofluid in a twin tube counter flow heat exchanger with internal fins. The study found that with a higher volumetric concentration of nanofluid, the finned tube heat exchanger had an 80-90% heat transfer rate more than the plain tube. As the Reynolds number increased, so did the Nusselt number ratio of the nanofluid with the base fluid. The study also found that the friction factor decreased, and pressure drop was greater in finned tube heat exchangers due to the fin shape. A correlation for the Nusselt number was developed using the Wilson plot approach.

This study by (Gnanavel et al., 2020) aims to enhance heat transfer in devices like air conditioners and radiators, employing a passive method in a double pipe heat exchanger. Various nanofluids, including titanium dioxide and copper oxide, were investigated to boost thermal conductivity. Circular fin inserts were utilized to increase heat transmission by inducing flow resistance and spreading fluid over the surface. The research analyzed the thermal and flow fields of circular-finned nanofluids in the heat exchanger, employing the finite volume approach and ANSYS 15.0 for numerical simulations of momentum and energy equations.

(Aghayari et al., 2020) enhanced heat transfer in a DPHE using Fe_2O_3/water nanofluid and twisted-tape inserts. Nanofluid concentrations of 0.08 and 0.1 percent were chosen for their high heat conductivity. The twist ration of twisted tapes ranging from 2.5 to 5.2 were employed. Both inserts and nanoparticles augmented heat transmission and the Nusselt number, particularly at high Reynolds numbers. The combined use of nanofluid with twisted tape boosted the Nusselt number by 103.45 %, with minimal change in the friction factor. They utilized a neural network to model the Nusselt number.

(Dalkılıç et al., 2021) found that the diameter of heat exchanger pipes significantly affects flow characteristics, costs, and total heat transfer. As fin size increases, so do the hydraulic diameters of the annulus and heat duty. The study suggests considering the number, shape, and size of fins during design. It also found that the type of working fluid and cleanliness affect heat transfer. While increasing the number of fins reduces the total tube count, it also increases pressure drops and pumping power. Nanofluids notably impact cost and ideal annulus side velocity.

(Mozafarie et al., 2021) analyzed a nanofluid's thermal and flow properties in a circular finned double pipe heat exchanger through a 3D CFD model. They explored Al_2O_3 nanoparticles in both Newtonian and non-Newtonian turbulent flows. Circular fins enhanced heat transmission by 36% for Newtonian and 30% for non-Newtonian nanofluids. Increasing Al_2O_3 concentration and Reynolds number raised the Nusselt number. However, combining fins and nanoparticles degraded thermal performance of non-Newtonian fluid because of the increment in pressure drop. They suggest avoiding annulus inserts when introducing nanoparticles to non-Newtonian fluid.

(Singh and Sarkar, 2021) conducted research on the hydrothermal properties of an Al_2O_3 + TiO_2 hybrid nanofluid in a double-tube heat exchanger with modified V-cuts twisted tape inserts. They found that the Nusselt number and friction factor increased with the entrance temperature of the nanofluid, depth ratio, and decrease in width and twisting ratios. The greatest increases, 132% for the Nusselt number and 55% for the friction factor, were observed when compared to a tube without twisted tape. The entropy generation ratio and thermal performance factor values were higher than unity for all modified twisted tape inserts with the hybrid nanofluid.

(Jalili et al., 2022) studied convection heat transfer in a double-tube heat exchanger with fins. They found water-aluminum oxide nanofluid to be more effective in heat transfer than water, pure water or titanium dioxide. The heat transfer coefficient increased with nanofluid concentration, making rectangular and curved fin heat exchangers 81% and 85% more efficient, respectively. The pressure drop was reduced due to the increased heat transfer coefficient.

(Gholizadeh et al., 2022) used a diesel engine and a heat exchanger to reduce exhaust temperatures and greenhouse gases. They experimented with different fin configurations and nanofluids. Increasing fin curvature and height reduced exhaust temperature by 7.0% and 5.80%. The fin arrangement and quantity had a greater impact on heat transmission than the shape of nanoparticles.

(Hamza and Aljabair, 2022) examined the thermal performance of a modified heat exchanger tube with various vortex generator inserts, including two types of twisted tapes and a hybrid nanofluid. A tube equipped with a double V-cut twisted tape and hybrid nanofluid exhibited enhanced thermal performance compared to a plain twisted tape. The increased vortex flow facilitated faster heat transfer. Thermal performance factors rose from approximately 1.068 for plain tubes to 1.33 and 1.37 with the addition of plain and double V-cut twisted tapes, respectively. Results remained consistent across numerical and experimental scenarios, with a maximum error of 9.7%.

(Hasan et al., 2023) conducted a numerical analysis of heat transfer improvement in a double pipe heat exchanger with an enlarged surface and Alumina nanofluid. They used Computational Fluid Dynamics and Solid Works for the model, and the Semi-Implicit Method for Pressure Linked Equations for solving the governing equations. The study found that using a finned tube heat exchanger improved performance, with the convective heat transfer coefficient increasing as both Reynolds number and volume concentration rose. Specifically, when the volume concentration was 5 percent, the thermal conductivity increased by 20 and 4.7 percent, respectively.

Double Pipe Heat Exchanger with Fins

Extended surfaces, or fins, facilitate heat transfer through conduction and convection, using fins with a Double-Pipe Heat Exchanger (DPHE) falls under the category of passive heat transfer enhancement. Fins are attached to the outer surface of the inner tube or the inner surface of the outer tube to increase the heat transfer surface area, thereby improving heat transfer efficiency, although radiation can also play a role. While fins generally enhance heat transfer rates, this isn't always the case due to various factors. To address this, an effectiveness factor compares the heat transfer rate of a finned surface to that of a smooth surface without fins, aiding in understanding the true impact of fins on heat transfer.

$$\varepsilon_f = \frac{q_f}{hA_{c,b}\theta_b} \tag{5}$$

where $A_{c,b}$ is the cross-section area of the fin base. And to use the fins correctly, the criterion $\varepsilon \geq 2$ must be valid (Chavan, 2023).

(Mainardes et al., 2013) accomplished an experiment to reduce pumping power for air supply through a finned tube bundle. In turbulent flow (RE_{2b} range: 2,650 to 10,600), pressure decreases are linked to eccentricity. Experimental optimization showed that pumping power can be reduced by adjusting tube spacing and eccentricity in finned circular and elliptic tubes. The best elliptical designs exhibited 5 to 10 percent pumping power savings compared to circular tubes.

(Barga and Saboya, 1999) investigated longitudinal rectangular fins in the annulus of a DPHE, focusing on heat transfer, pressure drop, and efficiency under turbulent flow conditions. Water and air were used as working fluids in the inner tube and annulus, respectively. Their numerical analysis employed two-dimensional heat transfer simulations. Fin efficiency was correlated with dimensionless parameters like D* and H*, representing ratios of tube diameters and fin dimensions. The ratio of Nusselt numbers for finned and smooth annuli was consistently below unity and decreased with increasing Reynolds number, indicating fins negatively impacted heat transfer in the annulus.

(Kumar et al., 2015) investigated Double-Pipe Heat Exchangers (DPHEs) experimentally and numerically, analyzing their performance with longitudinal fins of rectangular, triangular, and parabolic configurations. Longitudinal rectangular fins exhibited superior heat transfer efficiency in comparison with other shapes, while longitudinal parabolic fins incurred lower pressure drops. They emphasized the importance of a higher mass flow rate for the hot fluid compared to the cold fluid for optimal performance.

(Yakar & Karabacak, 2015) experimentally studied the thermal performance of perforated finned heat exchangers with varying rotation angles (u). Six-millimeter-diameter holes on circular fins were used to enhance convection heat transmission by minimizing the boundary layer thickness. Trials at six angles revealed that the 60° angle position yielded an 18% higher efficacy and a 1.16% lower pressure drop compared to other angles. This suggests 60° as the optimal angular position. The data also indicated that increasing the number of transfer units correlates with improved efficacy.

(Hasan, 2015) examined the accuracy of mathematical equations using computational fluid dynamics (CFD) for twin-pipe heat exchangers. Thinner fins exhibited better accuracy in water line exit temperature, while thick fins showed greater discrepancies between CFD and mathematical calculations. The study identified higher exhaust heat temperatures than predicted mathematically and elevated water output temperatures compared to CFD results. It concluded that the k-epsilon RNG turbulence model is the most suitable tool for evaluating heat transport in twin-pipe heat exchangers.

(Syed et al., 2015) examined heat transfer in a novel finned double pipe heat exchanger (DPHE) with longitudinal fins of varying tip thickness using DG-FEM. The study introduced tip thickness as a novel parameter, ranging from 0 to 1, representing fin geometries from triangular to rectangular. Results showed significant improvements in Nusselt number, with up to 178% and 89% gains compared to rectangular cross-sections, and 9.5% and 19% compared to triangular cross-sections. The findings underscored the importance of this parameter in optimizing DPHE design, leading to reduced cost, weight, frictional loss, improved heat transfer, and enhanced energy efficiency. This highlights its pivotal role in heat exchanger development.

(Hamzah and Nima, 2020) investigated the impact of copper foam fins on a double-pipe heat exchanger by experimentation. The setup included concentric copper and Perspex pipes with 40 PPI copper foam fins at a 30° angle. Tests covered Reynolds numbers from 616 to 2343, maintaining a constant water flow rate and varied water temperatures. Results revealed peak heat transfer coefficients and Nusselt numbers with increasing Reynolds numbers, notably in counterflow with copper foam fins. Pressure decrease was insignificant despite improved heat transmission. Efficacy doubled with copper foam fins, with counterflow configuration outperforming parallel flow.

(El Maakoul et al., 2020) examined a double pipe heat exchanger (DPHE) with split longitudinal fins (SLF) on the annulus side, disrupting the boundary layer. Computational fluid dynamics (CFD) simulations investigated various fin split intervals under laminar flow, using engine oil. Comparisons between SLF and traditional LF configurations were made regarding fluid flow, heat transfer rate, and pumping power. SLF designs displayed an entry region-like effect, leading to higher heat transfer rates (31% to 48%) compared to LF setups for the same pumping power and unit weight.

(Sivalakshmi et al., 2020) investigated the impact of helical fins on the performance of a twin-pipe heat exchanger. Heat exchangers with helical fins on inner pipes surpassed those with plain pipes in heat transfer rate, coefficient, and overall efficacy. Experiments varied the hot fluid flow rate while maintaining a constant input temperature. Results showed increased heat transfer coefficient with fins, resulting in improved average heat transfer rate (38.46%) and efficiency (35%) at higher flow rates.

(Mohsen et al., 2021) studied heat transfer in a twin-pipe heat exchanger with circular, helical, and interrupted rectangular fins. Experimental findings indicated that diverse fin designs increased the heat transfer coefficient, dependent on Reynolds numbers of both fluids. Rectangular fins exhibited the greatest heat transfer enhancement, while circular fins showed the least improvement. Circular fins resulted in the lowest pressure loss, whereas rectangular fins showed the highest pressure loss.

(Myong et al., 2022) examined heat exchangers with oval tubes in varying dimensions and pitches, comparing them with round tube samples. Increasing fin pitch raised the f factor but had no impact on the j factor, while more tube rows decreased both factors. Oval tubes generally outperformed round tubes, especially with smaller diameters. Larger oval tubes performed poorly due to significant pressure drops. The study developed correlations for j and f based on collected data.

(Rao et al., 2008) devised a versatile model for twin-pipe heat exchangers, considering internal or external fins. Their semi-empirical-numerical method integrates turbulent forced convection and conduction, aligning well with existing literature. With fins, the Nusselt Number decreases, yet the overall heat transfer rate rises owing to increased total heat transfer per unit area.

(Omkar et al., 2014) enhanced a twin-pipe heat exchanger by adding helical fins on the inner tube's outer surface and inducing turbulence through inner tube rotation. With a constant helical fin pitch, convective heat transfer coefficients were measured in counterflow mode using water and glycerol. The helical fins augmented heat transfer area, while inner tube rotation facilitated fluid mixing. Compared to a stationary tube with helical fins, the Nusselt number increased by up to 64% at 100 rpm, showcasing improved heat transfer efficiency.

(Taborek, 1997) investigated smooth and rectangular-finned double pipe and multi-tube heat exchangers to determine optimal operating conditions. Hot water circulated within the inner tube, while cold water flowed through the annulus. Experimental validation was conducted solely for the smooth DPHE, followed by numerical simulations for modified DPHEs with rectangular, triangular, and parabolic fin geometries.

(Kahalerras and Targui, 2008) investigated heat transfer enhancement in DPHEs using porous fins on the outer surface of the inner tube employing the Brinkman-Forchheimer Extended Darcy model for porous regions. Results were valid only when both tubes had identical fluids with equal mass flow rates. They extensively studied the effects of parameters like fin height, spacing, Darcy number, and thermal conductivity ratio on heat transfer and pressure drop. The highest average Nusselt number was observed with lower porosities and taller fins when the thermal conductivity ratio was set at 1.

(Syed et al., 2015) studied laminar convection in a DPHE with changing fin-tip thickness, a parameter defined for the initial time. Using Discontinuous Galerkin Finite Element Method (DG-FEM) in their simulations, they evaluated DPHE effectiveness considering pressure drop, Nusselt number, and j-factor. With rectangular cross-section fins, the increment of Nusselt number and j-factor is 178% and 89%, respectively, and for triangular cross-section fins, the increments were 9.5% and 19%. They found a strong correlation between fin-tip angle, number, and height of fins, emphasizing the parameter's significance in DPHE design for improving cost, weight, and friction loss.

(Sahiti et al., 2008) conducted a study on reducing entropy production in a pin-finned DPHE . They explored the effects of different flow lengths and pin dimensions within the heat exchanger at various Reynolds numbers. Experimental analysis of heat transfer and pressure drop properties was conducted with water and air as working fluids in the inner tube and annulus, respectively. The findings favored a larger number of passages with reduced pin heights over less passages with larger pin heights for optimal performance.

(Iqbal et al., 2015) investigated optimizing longitudinal fins to enhance conjugate heat transfer, exploring geometries like rectangular, parabolic, and trapezoidal. Using a numerical method with genetic algorithm and Discontinuous Galerkin Finite Element Method (DG-FEM), they optimized fin shapes with Nusselt number as an objective function. Findings were improved based on equivalent and hydraulic diameters, revealing a 289% increase in heat transfer coefficient for equivalent diameter and a 70% rise for hydraulic diameter.

DHPE with wired coils

(Akpinar, 2006) examined heat transfer and exergy loss in a concentric DPHE equipped with wire coils. Experimenting with hot air and cold water, he found that increasing helical number and decreasing swirl pitch raised heat transfer and exergy loss. Nusselt number, friction coefficient, and exergy loss were notably higher compared to smooth tubes, with increases of 2.64, 2.74, and 1.16 respectively. The counter flow configuration with the highest helical number (h_n = 137) exhibited the highest heat transfer rates as in Figure 4

(Naphon, 2006) studied wired coil inserts in a concentric DPHE with water. He found that these coils significantly enhance heat transfer in laminar flow. However, this enhancement diminishes as Reynolds number increases, as shown in figure 5.

Effect of Fouling in Double Pipe Heat Exchangers

Fouling significantly impacts the performance and efficiency of double pipe heat exchangers (DPHEs). Fouling refers to the accumulation of unwanted materials on the heat transfer surfaces, leading to reduced heat transfer efficiency and increased pressure drop.

Types of Fouling

Al-Fahed et al. (1992) has identified particulate fouling as a common issue in DPHEs. This type of fouling is caused by the deposition of suspended particles from the fluids onto the heat transfer surfaces.

Flemming et al. (1998), biofouling results from the growth of microorganisms such as bacteria and algae on the surfaces, which can significantly impact heat transfer performance.

Epstein (1983) discusses chemical fouling, which occurs due to chemical reactions between the fluid and the heat exchanger material, leading to the formation of scale or other deposits.

Research by Malayeri et al. (2005) highlights corrosion fouling, which involves the degradation of heat exchanger surfaces due to chemical reactions with the fluid, leading to the formation of corrosion products.

Muller-Steinhagen (2000) notes that crystallization fouling results from the precipitation of dissolved salts or minerals when the fluid becomes supersaturated.

Effects of Fouling

Fouling can significantly impact the thermal and hydraulic performance of DPHEs.

Wang et al. (2009) show that fouling can lead to substantial reductions in heat transfer rates. The buildup of fouling layers acts as an insulating barrier, reducing the overall heat transfer coefficient and decreasing the efficiency of heat transfer between fluids.

Al-Fahed et al. (1992) studied the increased pressure drop, where fouling can obstruct fluid flow, leading to increased pressure drop across the heat exchanger. which requires higher pumping power to maintain the desired flow rates.

Muller-Steinhagen (2000) discuss the economic impact of fouling, including reduced efficiency and increased energy consumption, the need for frequent cleaning and maintenance due to fouling increases operational costs.

Malayeri et al. (2005) noted that Persistent fouling can cause mechanical stress and damage to the heat exchanger surfaces, leading to a shortened operational lifespan of the equipment.

Other Types of turbulators in DPHEs

As it’s known, the majority of the researches on turbulators are done experimentally. Each type of turbulator offers a trade-off between improved heat transfer and increased pressure losses, in the following there are some studies about other kinds of turbulator.

(Yildiz et al., 1996) conducted an experimental study on fluid rotation's impact on a DPHE using propellers. They observed a 250% increase in heat transfer rate compared to a smooth tube, with pressure drop rising by 500-1000%. These effects varied with Reynolds number and the number of propellers (5 and 10). However, the study did not determine the optimal number of propellers or their dimensions and rotating angle.

(Durmus, 2002) conducted an experimental study on a concentric DPHE with a snail entrance, analyzing heat transfer and exergy loss. Cold air and hot water were used as working fluids. The snail vortex generator had a lesser impact on heat transfer at low Reynolds numbers due to air speed. Implementation of the snail entrance enhanced heat transfer by inducing swirling flow, with Nusselt numbers increasing by 85-200% in counter flow. Pressure losses were 110% higher than smooth tubes for both flow configurations. Counter flow was deemed the most optimal based on exergy loss criteria.

(Akpinar and Bicer, 2005) investigated perforated turbulators in a DPHE's inner tube. Hot air and cold water were used as fluids. They examined the impact of hole number, diameter, and configuration (zigzag, linear), finding heat transfer rates rose with more holes and smaller diameters. Maximum Nusselt number raise reached 130% more than smooth tubes as shown in figure 6.

(Eiamsa-ard et al., 2008) analyzed louvered strips' impact on a DPHE with hot and cold water. Two configurations, backward and forward, were studied. Compared to a smooth tube, forward configuration increased Nusselt number and friction factor by 284% and 413%. Backward configuration showed increases of 263% and 233%. Forward configuration also improved performance evaluation criteria by 9-24%.

(Zhang et al., 2012) explored heat transfer improvement in a DPHE's shell side using helical fins and vortex generators. Steam and cold air were the working fluids, with four vortex generator geometries tested. The study found that delta wings provided the highest heat transfer improvement for each unit area, followed by delta winglet pair, rectangular wing, and rectangular winglet pair as shown in figure 7.

(Alkam and Al-Nimr, 1999) investigated the impact of porous substrates in a DPHE to enhance its performance. Inserted on each side of the inner tube, they increased heat transfer rates together and the configurations of counter flow. This enhancement was particularly noticeable with greater thermal conductivity ratios, stated as the ratio between effective thermal conductivity in the porous domain and the conductivity of fluid thermal.

(Al-Kayiem and El-Rahman, 2011) conducted a numerical study on applying ribs as turbulators in DPHEs, a method for thermal enhancement. This appears to be the sole study focusing on ribs for this purpose.

Compound method

The combination of fluid vibration and wire coils represents a compound heat transfer enhancement method, integrating both active and passive approaches. Numerous studies have explored this method's application in heat exchangers, showcasing its potential for improving heat transfer efficiency.

(Omkar et al., 2014) investigated the use of helical fins on the outer surface of a rotating inner tube in a study. Water and glycerol were used as working fluids in the inner tube and annulus respectively. They found a significant 64% increase in Nusselt number when the rotation of inner tube was 100 rpm compared to when it remained constant.

Trade-off between Heat Transfer Enhancement and Pressure Drop

Enhancing heat transfer in double pipe heat exchangers (DPHEs) often leads to increased pressure drops, impacting overall efficiency. Active methods like rotating inner tubes improve heat transfer but raise friction and pressure drop. Passive methods, including twisted tapes and fins, also enhance heat transfer while increasing flow resistance. Nanofluids improve thermal conductivity but increase viscosity, leading to higher pressure drops. Optimizing the design and operating conditions is crucial to balance these trade-offs, achieving high thermal efficiency without excessive operational costs.

CONCLUSION

This comprehensive review has examined various active, passive, and compound methods for enhancing heat transfer performance in double pipe heat exchangers (DPHEs). Passive techniques, which involve geometrical modifications or inserts, have been extensively studied and proven effective in improving heat transfer rates.

The use of twisted tapes, particularly with modifications like spacing or varying twist ratios, exhibited significant enhancements, reporting up to 40% higher heat transfer compared to smooth tubes. Finned surfaces of different geometries, such as rectangular, triangular, and parabolic fins, also showed notable improvements. observing up to 178% and 89% increases in Nusselt number for rectangular and triangular fins, respectively, compared to plain tubes.

The incorporation of nanofluids as working fluids has emerged as a promising passive method, leveraging the enhanced thermal conductivity of nanoparticle-fluid suspensions. Studies have reported substantial heat transfer augmentations, achieving up to 80-90% higher heat transfer rates using Fe_3O_4-water nanofluid in a finned tube heat exchanger compared to plain tubes.

Compound methods, combining active and passive techniques, have demonstrated synergistic effects in further improving heat transfer performance which observed a remarkable 64% increase in Nusselt number when employing helical fins on a rotating inner tube compared to a stationary configuration.

While most techniques lead to improved heat transfer rates, they often result in increased pressure drops, necessitating a careful evaluation of the trade-off between heat transfer enhancement and pumping power requirements. Techniques such as employing nanofluid-filled porous fins, or optimizing fin geometries, as explored, offer promising avenues for minimizing pressure losses while maximizing heat transfer.

Overall, this review highlights the significant potential for heat transfer augmentation in DPHEs through various active, passive, and compound methods. The choice of technique depends on the specific application, operational constraints, and the desired balance between heat transfer enhancement and pressure drop penalties. Future research should focus on developing novel geometric configurations, exploring advanced nanofluids, and integrating multiple techniques to achieve optimal thermal-hydraulic performance in DPHEs.

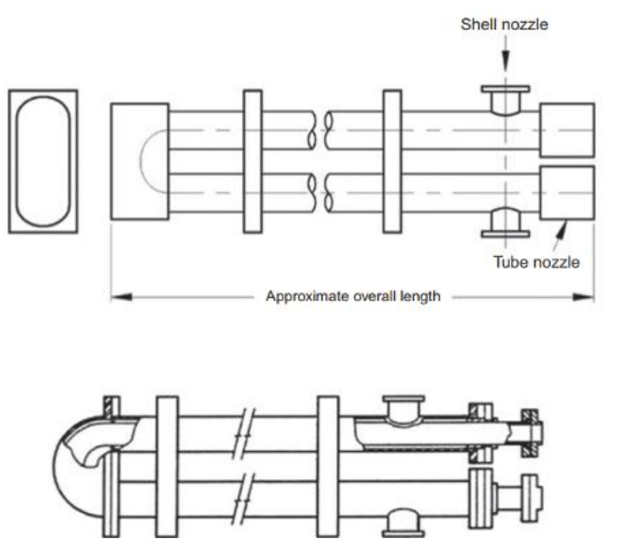

Fig.1. Simple schematic of double pipe heat exchanger (Robert and Perry, 1999)

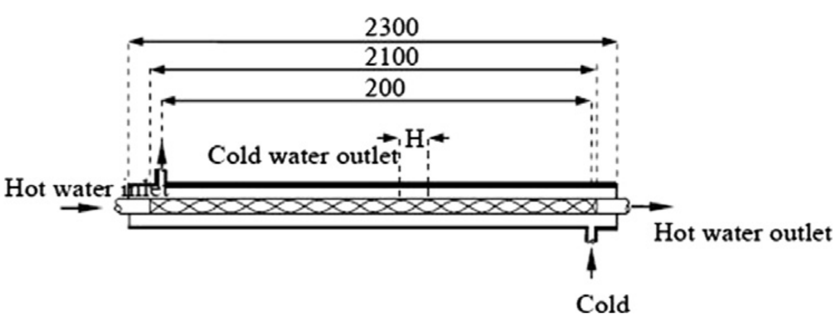

Fig. 2. Typical twisted tape DPHE (Naphon, 2006)

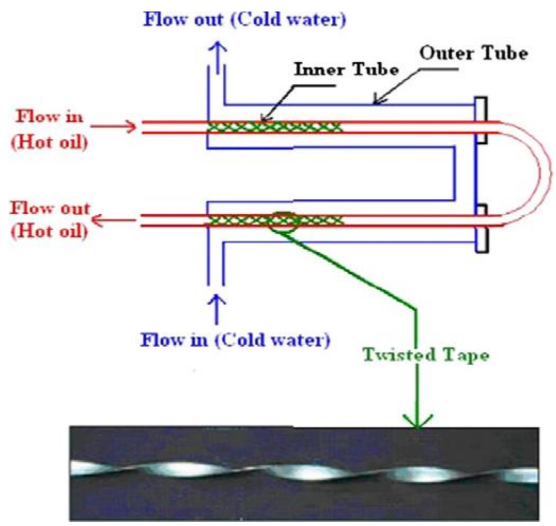

Fig. 3. Half-length twisted tapes DPHE (Yadav, 2009)

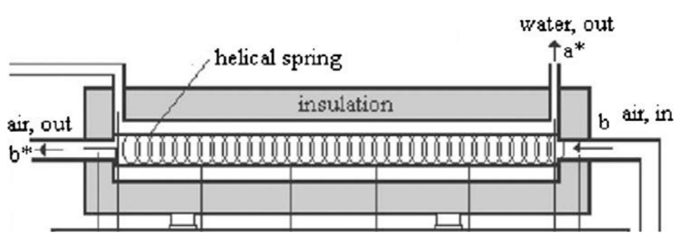

Fig. 4. Helical wires in DPHE (Akpinar, 2006)

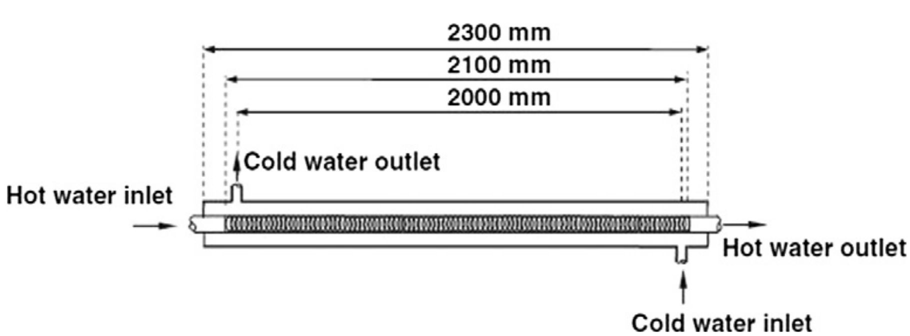

Fig. 5. Coil-wire insert in DPHE (Naphon, 2006)

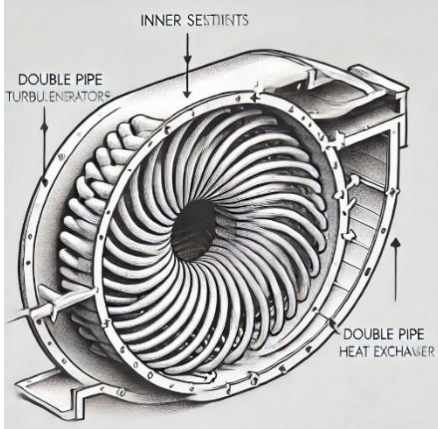

Fig. 6. Swirl parts in the entrance segment of the inner pipe of a DPHE (Akpinar and Bicer, 2005)

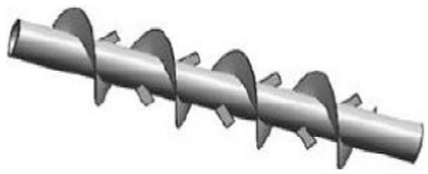

Fig. 7. The outer surface of the inner tube with vortex generators and helical fins on it (Zhang et al., 2012)

Table 1**.** Review study table of different authors for heat transfer improvement in DPHE.

Researcher / year	Num./ Exp.	Objective
Omidi (2017)	Num.	Reviewed experimentally and numerically studies to forced convective heat transfer occurring in DPHEs. Also study the enhancement of heat transfer performance methods.
Bahmani (2018)	Num.	Investigated the heat transfer and turbulent flow of water/alumina nanofluid in a parallel as well as counter flow double pipe heat exchanger. to enhance the Nusselt number and convection heat transfer coefficient.

Khalaf (2018)	Num.+ Exp	Enhanced heat transfer in double pipe heat exchanger with semicircular disc Baffles by using two parts, experimental work and Artificial Neural Networks (ANN) application
Gabir (2021)	Num. +Exp	Presents experimental and theoretical study to improve thermal energy exchange by the forced convective mode that happen in DPHE.
Singh (2022)	Num.	Focused on adopting different flow shapes to enhance heat transmission in double-pipe heat exchangers, while also taking heat transfer characteristics into consideration.
Sridharan (2022)	Num.	Grey relational analysis was used to increase the heat exchanger system's efficiency and cold-water output temperature (t2) (GRA).
Chavan (2023)	Exp.	Examined the utilization of nanofluids with distinct Plate Heat Exchanger (PHE) geometries. And its effect on the thermal performance on the system.
Vijayaragavan (2023)	Num.	Studied how a two-pipe heat exchanger with circular labyrinthine tunnels may improve heat transmission. also investigated the rectangular and triangular cavities with fixed labyrinth tooth thickness, height, and pitch, the effect of additional labyrinth structures on heat transmission characteristics.
Mainardes (2013)	Exp.	Minimizing pumping power required to supply air through a finned tube bundle configuration. The obtained results for the Reynolds number based on the smaller ellipse axis (RE_{2b}) ranging from 2,650 to 10,600
Yakar (2015)	Num.	Investigated the thermal performance of perforated finned heat exchangers with angle of rotation. Six-millimeter-diameter holes that were opened on each circular fin to reduce the thickness of the boundary layer
Hasan (2015)	Num.	Evaluating mathematical heat transfer effectiveness equations using CFD techniques for a finned double pipe heat exchanger.

Syed (2015)	Num.	Studied a unique finned twin pipe heat exchanger with longitudinal fins of variable tip thickness exposed to boundary conditions of constant heat transfer rate for the examination of fully developed laminar convective heat transfer.
Hamzah (2020)	Exp.	Assessed how adding copper foam fins to a double-pipe heat exchanger would affect the efficiency of heat transmission. The findings demonstrate that when the Reynolds number increases, the average heat transfer coefficient and the average Nusselt number rise as well, reaching their highest values when copper foam fins are inserted and when counterflow is operating.
Maakoul (2020)	Num.	Determined a double pipe heat exchanger (DPHX) with split longitudinal fins (SLF) on the annulus side for its thermo-fluid characteristics. Results show that for the same pumping power and unit weight, the heat transfer rates in annuli equipped with SLF are greater than those with traditional LF by 31% to 48%.
Sivalakshmi (2020)	Exp.	Examined how helical fins affect a twin pipe heat exchanger's efficiency. The heat transfer coefficient is raised with the addition of fins, according to the results. At higher flow rates, the average rate of heat transfer and the efficiency of the heat exchanger increase to 38.46% and 35%, respectively.
Mohsen (2021)	Exp.	Studied the heat transfer in a twin pipe heat exchanger with different heat exchange surface fin designs. Different fin geometries enhance heat transfer coefficient, with rectangular fins enhancing the most and circular fins minimizing it, with circular fins causing the lowest pressure drop.
Myong (2022)	Exp.	Examined two different oval tube diameters and two different tube pitches in common heat exchangers that use oval tubes. The study found that oval tube samples with smaller diameter tubes performed better, while larger diameter tubes showed poor performance due to large pressure drops.

Rao (2008)	Num.	Established a physically based model to assess HT and frictional loss for a twin pipe heat exchanger with internal or external fins under a range of real-world operating conditions. The addition of fins to double pipe heat exchangers decreases the Nusselt Number, but increases the heat transfer rate due to increased overall heat transfer per unit area.
Omkar (2021)	Exp.	Helical fins were added to the outer surface of the inner tube to improve the heat transfer properties of the twin pipe heat exchanger, and the rotation of the inner tube produced turbulence. Helical fins enhance heat transfer area and fluid particle mixing, resulting in a 64% increase in Nusselt number at 100 rpm compared to stationary inner tubes with helical fins.
Chandra Sekhara Reddy & Vasudeva Rao (2014)	Exp.	Investigated the friction and heat transfer properties of a TiO_2 nanofluid flowing in a twin pipe heat exchanger with and without helical coil inserts. The heat transfer coefficient and friction factor of nanofluid are significantly enhanced by 10.73% and 8.73% compared to base fluid, and further by 13.85% and 10.69% respectively.
Saeedan (2016)	Num.	Analyze the thermal performance of a 3D filtered tube and a helically baffled heat exchanger using nanofluids. The Nu Number increased with volume concentration in CuO/water and Cu/water nanofluid, while it decreased with volume concentration in CNT/water.
Magesh Babu (2017)	Exp.	Examined the thermal behavior, heat transfer rate, and friction factor of Al_2O_3/DI water nano fluids in a micro finned tube with tube helical inserts for different twist ratios. The micro fin tube with LR twist achieved maximum performance with a nano fluid concentration of 0.2%.
Baba (2018)	Exp.	Increased heat transfer via heat exchanger tubes' interior fins. The study shows that finned tube heat exchangers have a higher heat transfer rate of 80-90% compared to

		plain tube heat exchangers due to the higher nanofluid volumetric concentration.
Sheikholeslami (2019)	Exp.	Studied how the usage of fins and nanosized materials affected the performance of the discharging system in the current investigation. It found that by suing fines inside the pipes will increase performance and the size of nano-particles affect deeply on the heat transfer rate.
Gnanavel (2020)	Num.	A passive approach was employed to improve heat transmission in a heat exchanger using two pipes. The friction factor decreases with increasing Reynolds number due to fluid velocity, reducing thermal boundary layer and friction factor. Nano-fluids have larger thermal performance factors than water.
Aghayari (2020)	Exp.	Fe_2O_3/water nanofluid (20 nm) increased heat transmission in a double-pipe heat exchanger with twisted-tape inserts. Fe_2O_3/water nanofluid's higher heat conductivity makes use of it conceivable.
Dalkılıç (2021)	Exp.	The effects of different working fluid types, as well as unclean and clean instances, are investigated with regard to overall heat transmission. The finned design has a lower cleanliness factor and lower pressure drop compared to the bare design, resulting in higher fouling and increased costs. The optimal velocity value for pure fluids and nanoblends flowing in the heat exchanger at 80 kW is found.
Mozafarie (2021)	Num.	Examined the thermal and flow characteristics of a nanofluid in a double-pipe, circular finned heat exchanger. Circular fin enhances heat transfer by 36% and 30% for Newtonian and non-Newtonian nanofluid, respectively, while increasing Nu number by increasing Al_2O_3 volume concentration and Re number.
Singh & Sarkar (2021)	Exp.	The hydrothermal characteristics of an Al_2O_3 + TiO_2 hybrid nanofluid flowing in a double-tube heat exchanger with various modified V-cuts twisted tape inserts are studied. The study shows that decreasing twisting ratio, depth ratio, width ratio, and nanofluid

		inlet temperature leads to improvements in Nusselt number and friction factor.
Jalili et al (2022)	Exp + Num	A countercurrent, double-tube heat exchanger with fins working in turbulent flow was studied for convection heat transfer. Water aluminum oxide nanofluid improves convection heat transfer coefficient, with a 12% increase in concentration. Heat exchangers with fins show 81% and 85% better efficiency.
Gholizadeh (2022)	Exp + Num	Employed a shell-and-tube heat exchanger and a 3.7 kW diesel engine to decrease exhaust gas temperatures and lessen the effects of greenhouse gases. The arrangement and number of fins significantly impact heat transfer rate, while nanoparticle shape factor and nanofluid concentration significantly affect exhaust gas temperature.
Hamza & Aljabair (2022)	Exp.	Evaluated the thermal performance properties of a heat exchanger tube modification fitted with various inserts for vortex generators. The thermal performance factor of hybrid nanofluid in plain circular tubes and Reynolds numbers is 1.8%, increasing to 1.33 and 1.37 when twisted tape is inserted, with a maximum error of 9.7%.
Hasan (2023)	Num.	Investigated how a "double pipe heat exchanger" with an extended surface implanted on the outer side of the inner tube may benefit from the addition of "Alumina nanofluid" to boost heat transfer. A finned tube heat exchanger improved convective heat transfer coefficient and thermal conductivity by 20% and 4.7% at 5% volume concentration and Reynolds number increase.

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