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Research Article

Thermal Performance Augmentation of Double-Pipe Heat Exchanger-A Critical Review

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ABSTRACT

The increasing demand to enhance the efficiency of heat exchangers has sparked numerous investigations aimed at increasing heat transfer rates while simultaneously reducing the size and cost of industrial equipment. Among the various apparatus utilized in different industries, the double-pipe heat exchanger has garnered significant attention due to its simplicity and versatile applications. Over recent years, numerous meticulous and invaluable studies have delved into double-pipe heat exchangers. This review meticulously analyzes the developmental trajectory of this heat exchanger type while extensively discussing methods for enhancing heat transfer within these systems. In striving to present a comprehensive overview, the authors have meticulously gathered information on various enhancement methods, including active and passive. Recent studies exploring passive heat transfer augmentation methods in double-pipe heat exchangers have been summarized. These methods are summarized under surface modification (like dimples, vortex generators and protrusion), inserts (like twisted tapes and helical coil) and extended surfaces (like fins and baffles). The prime objective of the current study is to organize the literature related to combining different heat transfer augmentation methods. An additional section on alternating cross-sectional tubes used in double-pipe heat exchangers has been summarized, exhibiting increased vorticity without vortex generator devices. Longitudinal vortices are created throughout the tube's length, leading to a notable improvement in its thermal efficiency. Furthermore, detailed discussions on using Nanofluids in these heat exchangers are provided. Additionally, correlations, primarily focusing on the Nusselt number and pressure drop coefficient, are presented within this review. This comprehensive review is anticipated to offer valuable insights for future investigations in this field.

Introduction

In the contemporary era, heat exchangers (HX) are extensively employed in various industrial and engineering applications.

Engineers face a formidable challenge when devising the design for an efficient HX. The complexity stems not only from the necessity of conducting an accurate assessment of long-term performance and associated financial costs but also from the indispensable requirement for a comprehensive investigation into heat transfer(HT), Δp, and ξ, all of which entail rigorous labour. Upon the implementation of HT augmentation methodologies, there is a

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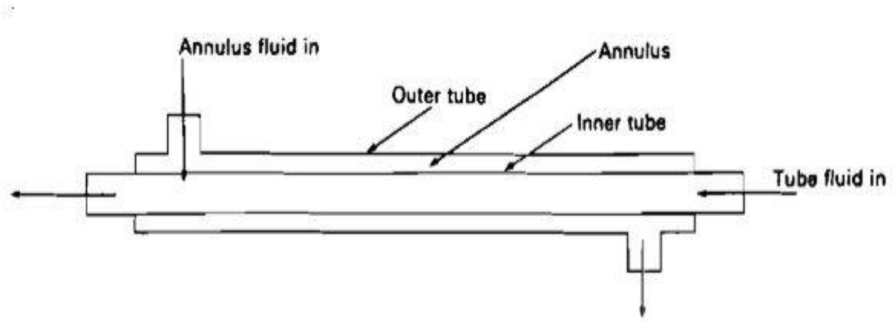

Fig.1 Simple DPHE [1]

concomitant increase in Δp, resulting in elevated pumping power requisites [1, 2]. It is, therefore, unequivocally stated that specific HT augmentation techniques may potentially exert adverse effects on attaining an optimal scenario encapsulating the HT rate and *Δp*. Consequently, the prudent selection of methodologies assumes paramount significance. Additionally, it is posited that attaining a high and optimal HT rate in various devices, including automobile engines, computers, electric power systems, and myriad other examples, is inevitable (refer to Tables 1 to 4).

A straightforward and practical HX commonly employed is the double pipe heat exchanger (DPHE) (see Fig. 1). This type of HX finds extensive application in the oil, chemical, gas, and food industries [3, 4].
Despite its relatively compact size, numerous meticulous studies have firmly established its utility in high-pressure environments. Moreover, it holds significant importance in scenarios requiring a broad temperature range. Notably, the DPHE plays a pivotal role in processes such as reheating, pasteurization, digester heating, preheating, and effluent heating, making it a preferred choice even among small-scale industries due to its cost-effectiveness in design and maintenance. Consequently, it is imperative to categorize previous research on this HX type to navigate the complexities of selecting the most suitable methodologies. To the best of the author's acquaintance, only a few review papers focusing on DPHE are available thus far, and addressing this gap constitutes one of the primary purposes of this review paper.

The movement within a DPHE can be categorized into two flow patterns: parallel or counterflow, as depicted in Fig.2. In parallel flow, both hot and cold fluids enter the DPHE from the same direction. Conversely, they enter from opposite sides and move in opposite directions in counterflow. In a counterflow HX, the cold fluid's exit temperature may surpass the hot fluid's, but it cannot exceed the hot fluid's entry temperature. The HT rate in a DPHE is directly linked to the LMTD. If operating conditions are identical, a counterflow HX consistently exhibits a greater LMTD than a parallel-flow HX, making it more efficient.

Given the straightforward design and widespread use of DPHE across industrial sectors, enhancing their ξ is a top priority, typically achieved through various methods to improve HT. For instance, artificially roughening pipe surfaces (or incorporating fins) can significantly boost HT rates under turbulent flow conditions. However, heightened surface roughness increases Δp and, consequently, more significant pumping power requirements. Bergles [5] described the pursuit of enhanced HT as typically framed within the realms of HT enhancement, intensification, or augmentation, which entails elevating the h_m as represented in Fig.3.

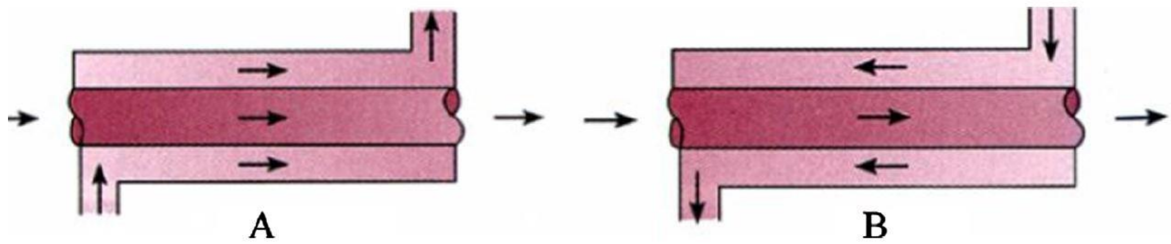

Fig.2 Parallel and counterflow DPHE [2]

HT improvement techniques are typically classified into three primary categories: active, passive and hybrid. Mohamad et al. [6] conducted an extensive review of DPHE, providing a detailed examination of the abovementioned techniques employed for augmenting HT. The researchers elucidated that active methods entail using external energy to augment HT. Examples

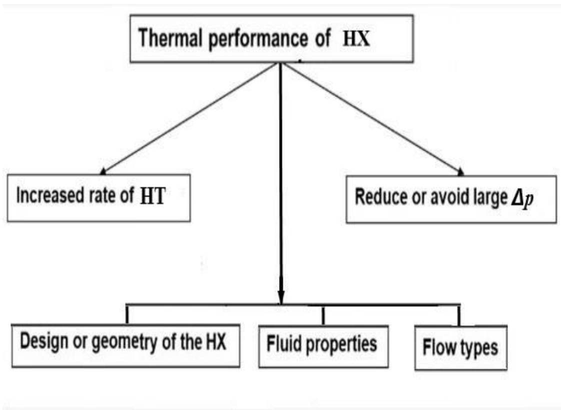

Fig.3. HT augmentation technique in DPHE

include the utilization of reciprocating plungers, the introduction of a magnetic field to disrupt flow, the application of surface or flow vibrations, and the implementation of electromagnetic fields. On the other hand, passive methods involve no external energy for enhancing HT. Instead, alterations in surface or geometry (8-23) are employed to bolster HT rates. Common modifications include extended surfaces such as fins (24-38) or the incorporation of twisted tape(TT) (42-60) inserts because of their uncomplicatedness, cost-effectiveness, and ease of installation and maintenance. While surface alterations augment the h_m and, consequently, the HT rate, they often lead to increased Δp.

The primary objective of this paper is to examine various methods employed to enhance thermal exchange between different fluids. A comprehensive review of several types of turbulators is conducted, including surface extensions (such as fins, strips, and winglets), rough surfaces (like corrugated pipes and ribs), and devices that induce swirl flow, such as twisted tapes, conical rings, entry snail turbulators, and coiled wires.

2. Heat Transfer Augmentation Using Tube Geometry Modification:

One passive method entails modifying the pipe's geometry, commonly involving adjustments to the HX's cross-section. Increasing the wall's surface area between the two fluids enhances the HX's ξ. However, this modification frequently leads to heightened Δp.

In recent times, numerous geometric alterations have been examined in scholarly works across both laminar and turbulent flow regimes.

Over the past twenty years, numerous studies have investigated the heat transfer and flow

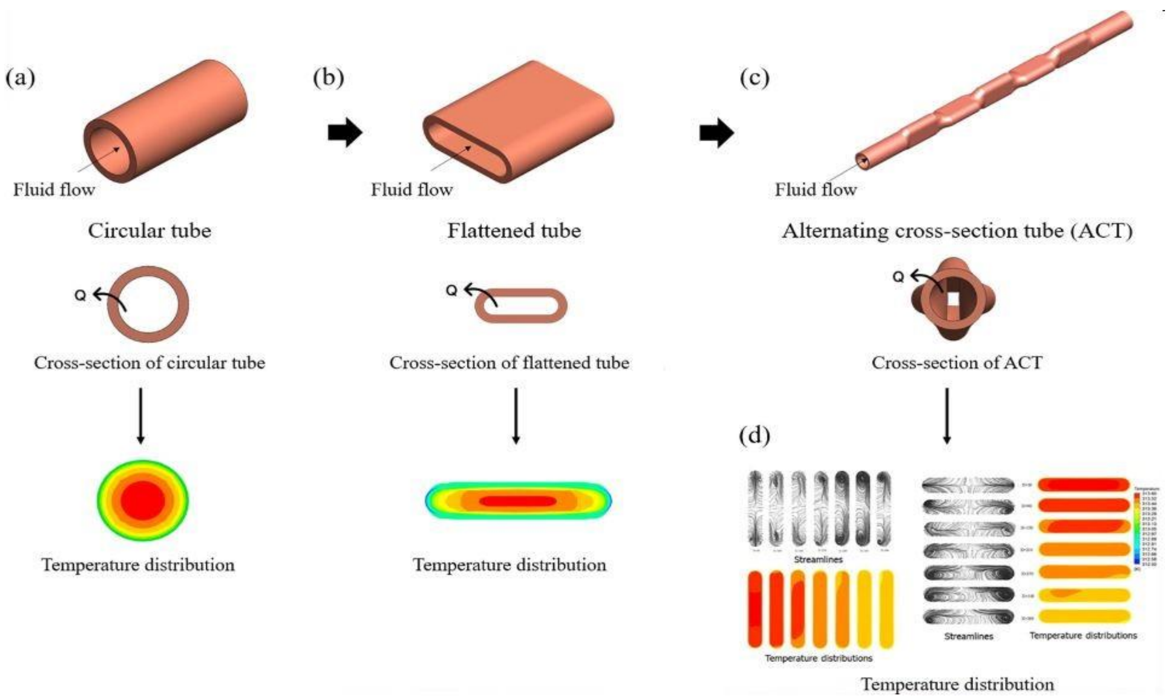

Fig.4. Conceptual design of ACT: (a) circular tube, (b) flattened tube, (c) ACT, and (d) velocity vectors and temperature distribution of ACT [8]

dynamics of tubes with alternating cross-sections in various configurations. Despite the diversity in cross-sectional shapes, the flow behaviours and vortex formations exhibited notable similarities. Geometric factors such as AR, PR, pitch length, transition length, alternating angle, phase shift, and overall length significantly affected the TPF of the alternating cross-section tubes (Fig.4a-d). Additionally, the flow characteristics within the annular region varied depending on whether the alternating cross-section tube was utilized as the internal or external tube [7, 8].

Recently, researchers have focused on twisted oval tubes, which offer a significant advantage in reducing Δp compared to tubes with inserts.

Yang et al. [9] delved into the impact of these twisted oval tubes on HT and *Δp* variation. Their findings revealed that tubes with a greater depth and smaller pitch of ovals exhibited enhanced HT and *Δp* fluctuations. TPF ranged from 1 to 3.6 for *Re* spanning 600 to 15,000. Tan et al. [10] demonstrated that twisted oval tubes induce swirl flow, enhancing velocity and temperature uniformity. These tubes demonstrated superior HT albeit with increased Δp compared to plain tubes, resulting in a TPF reaching up to 1.726.

Researchers have also delved into another approach: combining wall deformations, particularly in annular geometries, which have received less attention. The objectives of these techniques are to boost heat and mass transfer efficiency while reducing *Δp*. One such study was conducted by Zambaux et al. [11], who utilized numerical methods to examine an annular configuration featuring internal and external sinusoidal macro-deformed surfaces at a Re of 388. The cross-sectional profile transitioned gradually from circular to elliptical in alternating directions. The PEC achieved a peak value of 1.43 when the longitudinal phase shift of the tube was 1/8, indicating a 43% enhancement compared to a conventional smooth annular tube. A few of the recent studies have been tabulated in Table 1.

Abeer et al. [12] tried to improve the TEF of a dimpled tube by targeting regions with suboptimal heat transfer. He examined various dimple diameters and their in-line and staggered arrangements along the tube's length under turbulent flow (*Re* between 3000 – 8000), with single-phase flow with water as the coolant. The findings revealed that higher Re led to increased average Nu, greater Δp, improved TEF, and lower average thermal f across all models tested. Among the models, the staggered dimpled tube (Model B) achieved the most significant improvement in the Nu with TEF of 1.3, nearly doubling that of the conventional model.

Luo et al. [16] compared their numerical result with experimental values [21] of a DPHE with counter-twisting oval pipes, showing a discrepancy of 9.1% and 5.3% for *Nu* and *f*, respectively (Fig. 5a). They used the SIMPLE algorithm for Velocity-pressure coupling. At the same time, gradient, convection and diffusion terms are discretized by the least squares cell-based method, the second-order upwind and the central difference schemes, respectively. Tang et al. [18] used a variable direction twisted tube for HT augmentation, which validated their work from open literature (experimental) [22, 23], as seen in Fig5b, showed a mean deviation of Eu number (Eu=2*Δp*/ρμN) of 9.1%.

2.1. Extended surfaces

Fins remain among the most common enhancement techniques employed across various applications. They are regularly integrated into condensers, evaporators, and other heat exchange systems as highly efficient

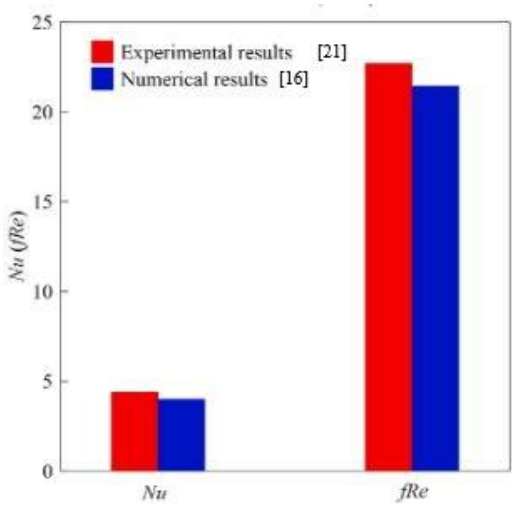

Fig.5a validation of numerical method. [16]

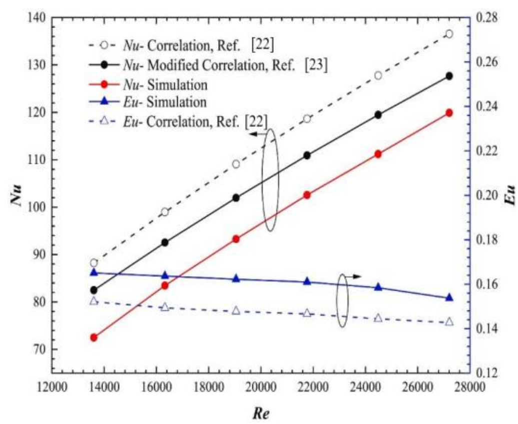

Fig. 5b Comparison of Nu number and Eu number. [18]

components for enhancing HT. Parameters such as fin efficiency, *f*, and h_m are crucial in assessing the performance of finned surfaces. Over time, researchers have explored numerous new designs to enhance the HT capabilities of fins

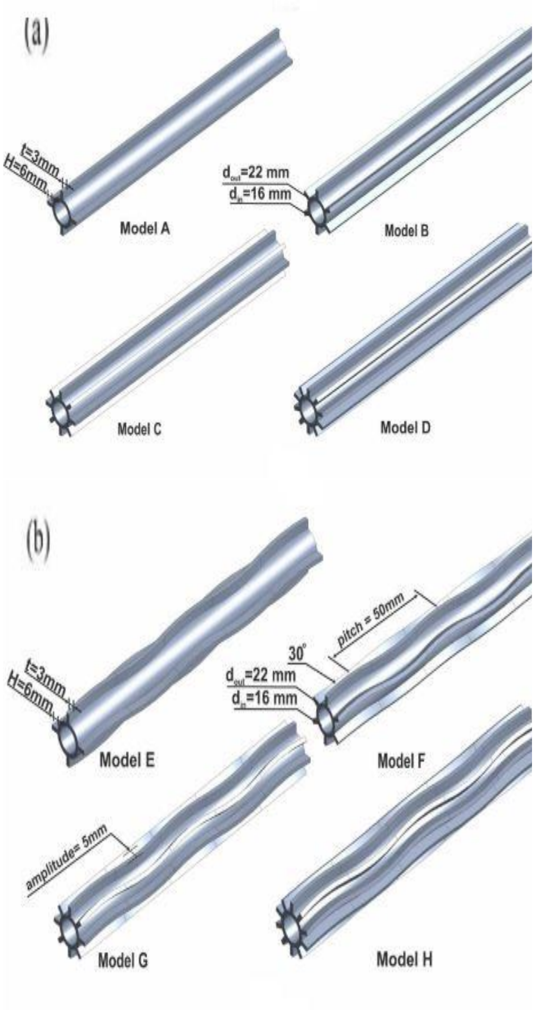

Fig.6 Inner tube of DPHE with (a) longitudinal (b) Wavy fin [27]

used in DPHEs.

Suryanarayana and Apparao [24] conducted experimental investigations into *Δp*, which were assessed in terms of pumping power within a DPHE. Their study focused on rectangular fins featuring interruptions, revealing a correlation between increased interruptions and elevated h_m. Syed [25] employed numerical simulations to explore heat exchange within a DPHE with rectangular fins. He suggested that considering the height and thickness of fins could enhance the correlation for the h_m alongside the hydraulic diameter. Further, to augment the HT efficiency of the shell side of a DPHE, Zhang et al. [26] equipped it with helical fins on its inner tube. VGs were strategically placed along the centerline of the helical channel: the HT performance and Δp characteristics of these improved HX. The helical fins within the annulus and its entire width were tested at various helical pitches. Wing-type or winglet-type VGs (delta or rectangular) were introduced to complement the helical fins. Results indicate that the shell side, enhanced by the combined HT augmentation approach, outperforms configurations with helical fins alone, particularly at shorter helical pitches. Hussein et al. [27] experimentally and numerically compared the TPF of DPHE with an alone, particularly at shorter helical pitches.

Hussein et al. [27] experimentally and numerically compared the TPF of DPHE with an inner tube equipped with fins of varying numbers (4-10) and orientation in longitudinal and wavy configurations, as seen in Fig.6. The numerical model was validated using experimental correlation is 14.5 and 3.5% for Nu and *f* (Fig. 7a), further, fig7b illustrates the

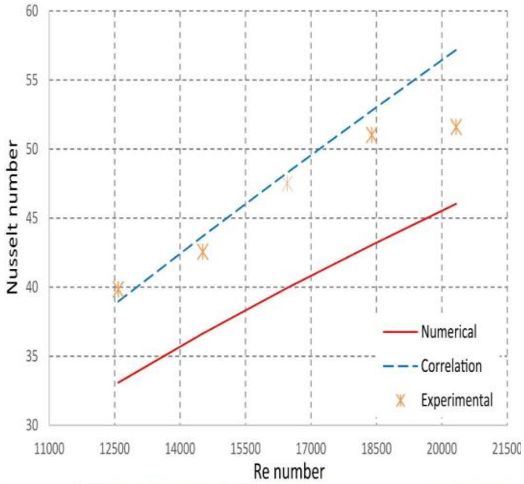

Fig 7a The validation of Nu of the conventional model with experimental results.[27]

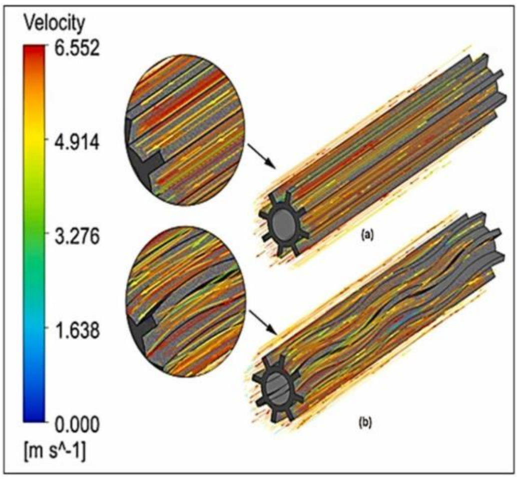

Fig. 7b. View of velocity streamlines for (a) longitudinal fins (b) wavy fins.[27]

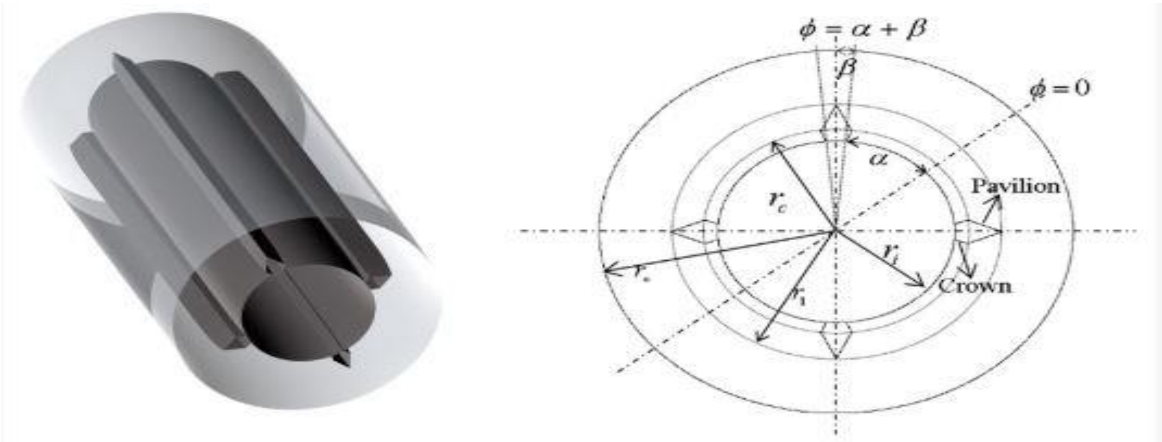

Fig.8a The DPHE with diamond-shaped fins along with its crossection[30]

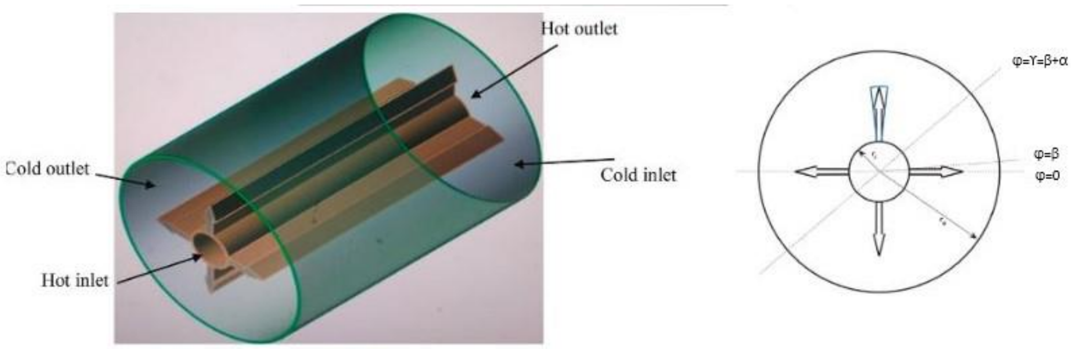

Fig.8b The DPHE with DPHX with arrow fins along with its crossection[31]

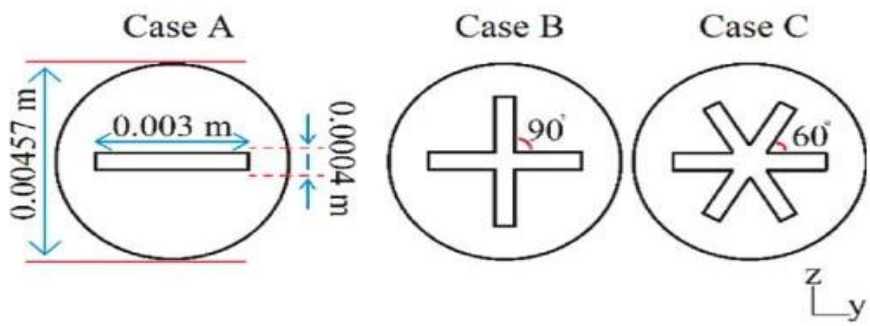

Fig.8c DPHE with different types of turbulator Case A is a rectangle, Case B and Case C, the cross sections of turbulators are obtained by connecting two and three rectangles to form a cross or semi-cross shape [32]

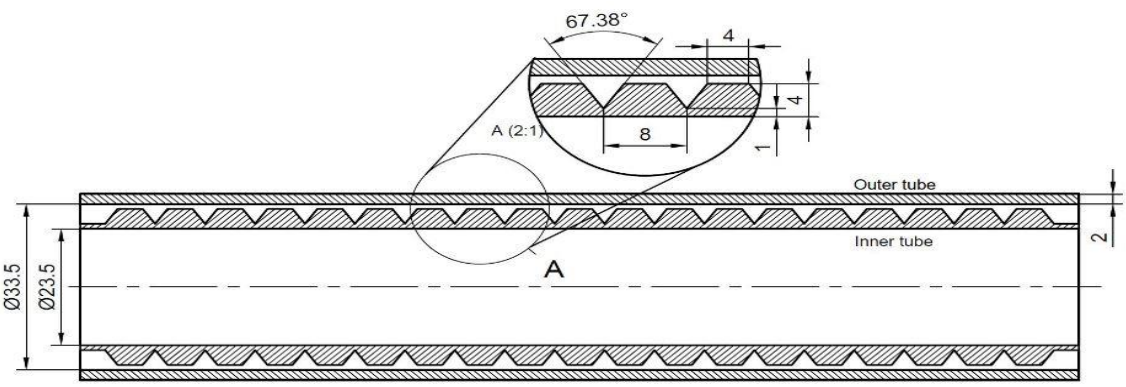

Fig.8d DPHE with triangular labyrinth heat exchanger.[34]

for two fin designs: longitudinal fins and wavy fins, at a mass flow rate of 7.5 g/s. Panel (a) depicts the configuration with longitudinal fins, while panel (b) shows the arrangement with wavy fins. This figure highlights how the air flows through the fins, with the wavy fins prolonging the air's exit path, thereby enhancing heat transfer efficiency. Notably, the optimal model among those studied emerged as the wavy fin configuration with 8 fins, exhibiting an overall efficiency of 1.33 compared to the traditional model. They further examined the performance of DPHE with various fin configurations, including longitudinal, split longitudinal (in-line and staggered arrangements), and semi-helical fins at angles of 90°, 180°, and 270°. A constant heat flux of 8000 W/m^2 was applied to the inner tube. Numerical analyses were conducted using ANSYS Fluent 2022 R1, assessing performance through the *Nu, Δp*, and *f* for the heat exchanger's tube side. The findings indicated that the fin type significantly affects the DPHE's performance. The semi-helical eight-finned design at a 90° angle outperformed others, achieving improvements of 1.47% overall performance and 66.76% in the *Nu* for the tube side [28].

Several numerical investigations have been undertaken in fin utilization within DPHEs. Among these, Kahalerras and Targui [29] delved into the HT augmentation of DPHE featuring perforated fins on the extended surface of the inner tube. Brinkman-Forchheimer Extended Darcy numerical model was used for perforated regions, with boundary conditions solved using the FVM. The authors emphasized that the obtained results were valid only when mf in both tubes were identical. This investigation extensively explored the effects of geometrical and thermal parameters such as perforation, fin height width and pitch, Darcy number, and kp ratio on the HT and Δp of the DPHE. Notably, in cases where the *kp* ratio was equal to 1, the maximum average Nu was achieved for minor porosities coupled with taller fins. In a recent numerical investigation, Syed et al. [39] explored laminar convection within a DPHE featuring variable fin-tip thickness. This thickness, expressed as the ratio of the fin-tip angle to the fin-base angle, ranged from 0 to 1, representing triangular to rectangular cross-section fin shapes. Notably, this parameter was introduced in the field. Employing the Discontinuous Galerkin Finite Element Method (DG-FEM), the ξ of the DPHE was evaluated considering Δp, Nu, and j-factor. For fins with rectangular cross-sections, substantial increases of 178% and 89% were observed in Nu and j-factor, respectively.

Conversely, the corresponding increases for triangular cross-sections were 9.5% and 19%. Additionally, the study highlighted the strong correlation between the fin-tip angle and the number and height of fins. This parameter was deemed crucial in DPHE design, offering favourable cost, weight, and friction loss changes. Other numerical investigations concerning finned DPHEs have also been conducted. A few of the recent geometric shapes numerically tested are shown in Fig 8. Fig8a shows a shaped fin, 8b shows a sphere fin, 8c shows multiple rectangular fins, and 8d represents triangular labyrinth fins. A few of the recent works are shown in Table 2.

Furthermore, several studies have deeply analyzed finned DPHEs through optimization processes, significantly contributing to the field. In one such study, Sahiti et al. [40] explored entropy generation minimization in a pin-finned DPHE across various HX flow lengths and pin lengths as functions of *Re*. The HT and Δp characteristics were experimentally analyzed using water and air as the working fluids in the inner tube and annulus, respectively. The study concluded that a larger number of passages coupled with smaller pin heights were preferable to fewer HX passages with larger pin heights. A few other HT argumentation methods have been discussed by Tavousi et al. [41].

3. Inserts

In conditions of turbulence, fluid doesn't flow smoothly but rather in an agitated manner. Turbulent flow doesn't create a protective layer on the channel walls, leading to rapid heat transfer. This turbulent flow induces mixing, reducing boundary thickness and enhancing heat transfer rates [42]. Implementing turbulence in a heat exchanger can enhance its efficiency. One method to induce turbulence is by employing TT. The insertion of TT inside the tube induces swirling flow, boosting turbulence within the tube wall and thus enhancing HT [43]. However, the presence of TT increases fluid flow disturbance, leading to higher Δp. Therefore, Therefore, designing TT is crucial for enhancing system thermal performance [44]. Moreover, optimizing the choice of working fluids in the HX system is another technique for performance

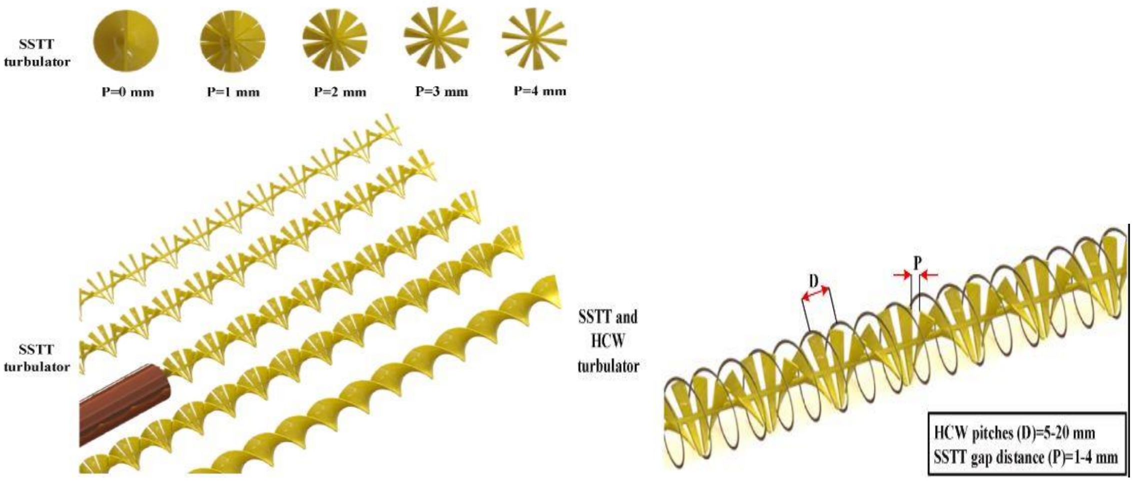

Fig.9. schematic of a tube with SSTT and HCW turbulator [50]

enhancement. Using a working fluid with high kp can significantly improve performance.

Naphon [45] pioneered investigating HT and Δp in horizontal DPHE fitted with TT inserts. He proposed a comprehensive set of correlations for the Nu and f with TT turbulators at different PR. Eiamsa et al. [46] explored the effects of inserting full-length and short-length TT tubes into DPHE. Their observations indicated that full-length TT tubes were more effective regarding the TEF, with a maximum TEF of 0.98 recorded at Re=6000. In addition to conventional TT turbulators, several researchers have sought to enhance the thermal efficiency of TT inserts through punching or perforation methods. Pesteei et al. [47] investigated the influence of perforation diameters on TT performance. Their findings revealed that increasing perforation diameter reduced the *Δp* and HT rates. Moreover, the TPF exhibited a positive correlation with perforation diameter, showing a 9.9% increase compared to a standard TT.

Singh and Kumar[48] experimentally studied HT and *f* characteristics of water flowing through a DPHE fitted with dimpled TT inserts of y=5.5, under Re ranging from 6000 -14,000 and dimple diameters between 3-7 mm. This peak Nu value is 1.50-1.10 times higher than a plain tube. Further, f was found to be directly related to the depth and diameter of the dimple, with the maximum *f* value observed at 7 mm and the maximum PEC obtained at a diameter of 5 mm.

Dandoutiya and Kumar [49] experimentally investigated the behaviour of the *Nu* and *f* within a DPHE utilizing W-cut TT inserts. *Re* ranging from 5500 to 16,000 were employed, with W-cut depths to twisted tape widths ratios of 0.2- 0.6, applied to twisted tapes of 10 mm width and 1 mm thickness. The effects of *y* vary between 5-15. Notably, the peak enhancements in the Nu and f were observed at a *Re* of 5500, with a W-cut depth of 6 mm and a *y* of 5, registering increases of 105.47% and 301%, respectively, with a maximum TPF of 1.35.

Luo et al. [50] introduce an innovative TT turbulator featuring a distinctive DNA-like shape, termed the unique shape TT turbulator (SSTT), as seen in Fig.9. Comprising segmented components, this turbulator facilitates fluid flow passage through the gaps while encouraging swirl flow along the HX. The PR of these segments ranged from 1–4 mm. Results indicate significant advantages of the innovative geometry over a conventional TT design. Optimal HT is achieved at a PR of 2 mm, leading to a 125% improvement over a plain tube. To further enhance thermal efficiency, a helical coiled wire turbulator is integrated alongside the tube with the selected SSTT. Findings reveal a 142% increase in the hm, escorted by a 960% elevation in Δp with these turbulators in place. Consequently, TPF reaches 1.31, marking a 20% augmentation compared to a standard TT turbulator. A few recent works on insert have been tabulated in Table 3.

Durmuş et al. [51]In this research, a passive approach was employed to enhance heat transfer in concentric DPHE by utilizing a snail positioned at the inlet of the inner pipe, functioning as a swirl generator. Cold ambient air was directed through the inner pipe during the experimental setup, while hot water flowed through the annular space. The study examined the impact of the snail on HT and *Δp* for both parallel and counterflow configurations. The findings were expressed as Nu concerning the Re, Pr, and the swirl angle. An enhancement of up to 120% in the Nu was achieved in the swirl flow under counterflow conditions with a swirling angle of 45°. Although the introduction of swirl flow due to the snail resulted in a slight increase in pressure drop, this effect was negligible compared to the significant improvement in heat transfer efficiency. A few additional geometric variations of inserts are shown in Fig. 10a, b and c.

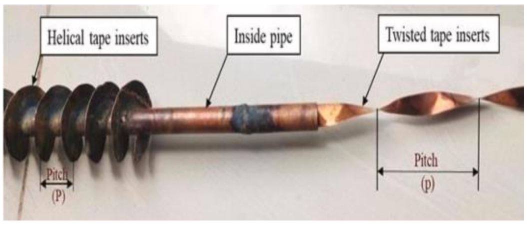

Fig.10a A photograph of twisted tape inserted in tube with helical tapes over tube.[52]

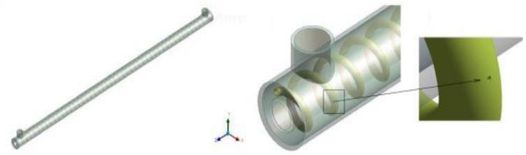
Fig.10b A turbulator with perforation on two sides of the axial direction.[54]

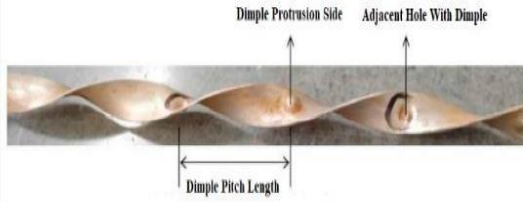

Fig.10c A photograph of twisted tape with dimple [55]

4. Nanofluids:

A high hm fluid is one way to increase the U of DPHE. In a study by Hussein [61], the thermal performance of AlN-ethylene glycol nanofluid was experimentally investigated within a DPHE, operating under Re between 500 - 1750, with vf ranging from 1 to 4%. The findings indicate a notable increase in f and Nu with higher vf. At the maximum vf, the f experienced a 12.5% enhancement, while Nu saw a 35% increase. Hasan et al. [62] conducted a pioneering investigation into the thermal efficiency of a DPHE employing Al2O3 and TiO_2-water nanofluids, considering both parallel and counterflow configurations. They demonstrated that the HT rate improved as the vf raised from 0.05 to 0.3%, attributed to the heightened thermo-physical properties of nanofluids, thereby augmenting the thermal efficiency of the HE. Moreover, the counterflow exhibited superior performance compared to the parallel flow arrangement for both nanofluids. In a separate study, Ponnada et al.[63] experimentally explored using SiC-distilled water nanofluids in a circular tube under turbulent flow conditions, considering vf between 0.04% - 0.1%. They observed that HT augmented by 3.38% to 36.74%, and the increase in f between 2.1% - 13.5% with higher particle ϕ.

Further, the type and the NP's size, shape and orientation are crucial in HT augmentation. In this context, Lin et al. [64] discovered that nanofluids containing rod-shaped nanoparticles exhibit more efficient heat transfer at higher Re due to their larger aspect ratio. They found that the shape and size of the particles play a crucial role in enhancing the thermal conductivity of nanofluids. Pak and Cho [65] concluded that

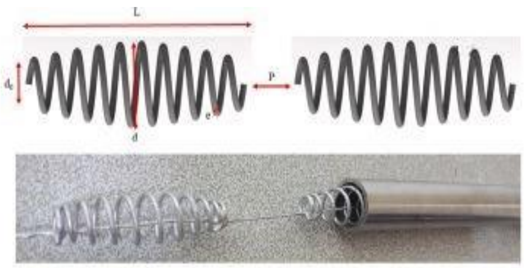
Fig.11 Photograph of conical wire inserts and their appearance inside the tube[68]

selecting particles with larger sizes and higher kp enhances HT performance. They observed that γ-Al_2O_3 and TiO_2 particles could be consistently dispersed well at pH values of 3 and 10, respectively.

Moreover, they noted that the *Nu* increased with higher vf and Re, with kp being the primary factor influencing HT performance. Dayou et al. [66] compared the thermal performances of multiwall CNT and graphene nameplate (GnP) nanofluids. They found that the hm of GnP and m_f Additionally, Dayou et al. emphasized the importance of selecting the appropriate size and shape of CNT and NP concentration to enhance thermal performance. In contrast, El-Behery et al. [67] conducted a numerical examination of NP, finding that increasing the vf of NP (Al_2O_3, CuO, TiO_2, and ZnO) led to increases in HT and Δp.

They also found that the average hm and ξ increased significantly as the Re was raised. Oflaz et al. [68] developed a novel wire coil insert with distinct characteristics from previously suggested designs in this research. These newly engineered inserts were positioned within a tube at five different distances (see Fig. 11), ranging from 0 to 33.6 mm, while SiO_2-water nanofluids were tested at vol. % of 0.5–1.25%. A two-step method was employed to prepare the nanofluids, and experiments were conducted under turbulent flow conditions. The result showed HT performance was observed with conical wire inserts featuring a PR of 0, while the lowest f occurred with conical wire inserts at a PR of 4. The optimal PEC reached 1.75 at a Re of 3338 and a vol.% of 1.25 for conical wire inserts with a PR of 0. Additionally, Nanofluids significantly enhanced HT rates as the Re increased with higher volume concentrations.

In contrast, lower vol.% had a minimal impact on HT and Δp. Rahman et al. have discussed a comprehensive review of the use of Nanofluids [69]. A few of the prominent works have been tabulated below in Table 4.

Comparison

Various factors, including application requirements, cost, complexity, and desired efficiency, influence the selection of heat transfer augmentation techniques. Standard methods, such as extended surfaces and forced convection, are favoured for their simplicity and effectiveness, while advanced techniques like nanofluids may provide more significant enhancements for specialized applications. Each technique has its associated trade-offs, necessitating careful consideration to achieve optimal performance. A comparison of different passive heat transfer enhancement techniques is presented in Table 5.

Key Attributes mentioned are as follows:

- Heat Transfer Enhancement: Indicates the technique's effectiveness in improving heat transfer rates.

- Pressure Drop Impact: Reflects the change in fluid pressure due to the enhancement technique.

- Cost: Relates to the economic feasibility of implementation.

- Manufacturing Complexity: Evaluate the difficulty in producing the enhancement method.

- Thermal Stability: Assesses how well the technique maintains performance under varying thermal conditions.

- Applications: Lists typical uses for each technique.

5. Conclusions and prospects

The present review paper delves into experimental and numerical investigations centred around forced convective heat transfer within DPHEs. These heat exchangers hold significant relevance in industrial and engineering applications. Numerous studies underscore the imperative of augmenting heat transfer rates while minimizing friction factors, often through passive HT enhancement methods. Some studies have stated staggering enhancements, with HT rates soaring by up to 400% and pressure drop plummeting by as much as 1000% compared to smooth tubes.

Geometry alterations in DPHE stand out as another promising avenue for bolstering performance, warranting further exploration in future studies. In many investigations, secondary flow phenomena are pivotal contributors to heightened heat transfer rates. Certain studies have explored unconventional methods like employing coiled wires within the annulus of DPHE.

The authors propose that leveraging VG in conjunction with low-Pr fluids holds promise for enhancing heat transfer in annular spaces. While active enhancement methods remain underutilized in DPHEs, the authors advocate for closer scrutiny of this approach.

Additionally, the review explores the burgeoning interest in employing nanofluids within DPHE. Future endeavours should focus on integrating nanofluids with passive heat enhancement techniques, as this synergy has shown promise in addressing various challenges.

Recently, discontinuous swirl generators in tubular HX have been extensively studied [80-96], which can be implemented in DPHE as extended surfaces with turbulators or inserts with turbulators.

Despite progress in refining the structural parameters of DHPE, there remains a significant gap in the literature regarding the use of swirl generators and their effect on performance metrics—such as effectiveness, thermal resistance, and overall heat transfer coefficient.

Previous studies have thoroughly examined the impact of various inserts on heat transfer; however, there has been limited investigation into the synergistic effects of combining different passive heat transfer augmentation.

The active enhancement method has not been widely adopted in DPHE, suggesting that it warrants greater research attention. This review also highlights the increasing interest in using nanofluids in DPHE. Future research should prioritize the integration of nanofluids with passive heat augmentation methods, as this combination presents a promising solution to numerous challenges in the field.

Nomenclature

	Abbreviations
AR	Aspect Ratio
HX	Heat Exchanger
TT	Twisted Tape
MPCM	Microencapsulated phase change material
PEC	Performance evaluation Criteria
MLV	Multi-longitudinal vortices
NP	Nanoparticles.
TPF	Thermal performance factor
FVM	Finite volume method
NP	Nanoparticles
NTU	Number of Transfer Units
GPR	Geometric y
LMTD	logarithmic mean temperature difference
DPHE	Double-pipe heat exchanger
HT	Heat transfer
CNT	Carbon nanotubes
VG	Vortex generators
HTF	Heat transfer fluid
	Greek symbol
φ	Concentration
y	Twist ratio
v_f	The volume fraction of NP
Pr	Pranddtl number
ξ	Effectiveness of HX
β	Twist angle
	Symbols
m_f	Mass flow rate
v	Flow velocity
Re	Reynolds number
Δp	Pressure drop
kp	Thermal conductivity
h_m	Convective heat transfer coefficient

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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Table1. HT agumentation using tube wall deformation in DPHEs.

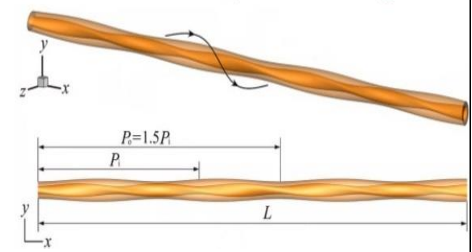
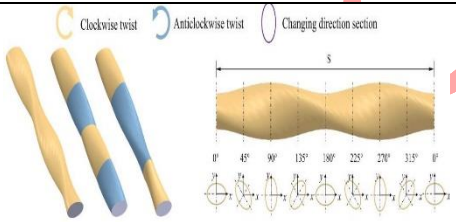
Authors	Configuration	HX Working fluids	Result
Quan et al [13]	The outer pipe diameter of 40mm was kept constant. In comparison, the geometry of the inner (diameter of 25mm) pipe was changed (AR decline), keeping the perimeter of the inner piper constant. Turbulent flow	Both hot and cold fluids, such as water, are used.	Inner pipe: Reducing AR increases flow velocity and *Δp,* but a rise in h_m is observed. Annuals: *Nu* reduces with a rise in *Re* but rises when AR reduces.
Ashagre & Rakshit [14]	The DPHX with helical tube. Outer circular pipe and an inner pipe of various geometric configurations. It is rectangular(RGC), circular, triangular, and has a mixed geometry groove cut.	MPCM slurry in inner helical pipe with 3, 4, 5 and 6-turns	A maximum TPF of 1.24 was observed for the RGC sample with 6 turns.
Hashemi an et al[15]	DPHE has an outer circular pipe and an inner conical pipe. Outer pipe: m_f=0.1666kg/s inner tube: (hot water) m_f = (0.16 -0.66)kg/s	Hot water is HTF in the inner pipe, and cold water is in the outer.	Nu rose by 63% while HT rate rose by 54%
Luo et al[16]		Annular side air is used. P_o =PR of the outer pipe P_i=PR of the inner pipe P_o/P_i = 1 - 2	*Nu* rises by 97%, with *f* rise by 43.7%. With P_o/P_i of 1.5, a maximum improvement in *j/f* of 63.8% is noted.
Yahiat et al. [17]	DPHE with outer wall sinusoidal and inner wall micro deformed, laminar flow(Re = 200 to 1000), and the effect of twisted core pitch on PEC were studied numerically.	Water as HTF	The sinusoidal outer tube generates longitudinal and transversal secondary flows in centripetal and centrifugal directions. Maximum PEC of 3.10 attained at smallest PR at Re=1000.
Tang et al.[18]		Variable direction twisted tube with various *β* and *v*	h_m twisted oval tube with β = 120° rises by 10.2%, Δp reduces by 7.8%, and *PEC* rises by 10.7%.
Liu et al [19]	DHPE with multi-waves internally spiral finned inner tube. Turbulent flow, Inner diameter of tube and fin angle on PEC were examined.	tubes made of stainless steel, with air and water used as working fluid.	The h_m and *f* of the finned tube are 8.67 and 5.84 times higher than the smooth tube.
Chen et al [20]	HT performance of HX with alternating horizontal and vertical oval cross-section pipes in parallel and counterflow	water	Alternating oval tubes simultaneously generate axial vortices in both the inner and outer tubes, increasing HT performance.

Table 2. Experimental works on extended surfaces on inner pipes of DPHEs.			
Authors	Configuration	Operating parameter	Result
Ishaq et al. [30]	diamond-shaped fin (design) attached to the inner tube of DPHX	numerical (FEM-based) method, Number of fin=4–32 , crown height = 30% of the annulus width, crown angel=6°,laminar flow	For optimum HT 4-8 fins with a height of 20-40% annulus width is recommended
Ashraf et al. [31]	The arrow-shaped fins attached to the inner tube of DPHX, number of arrow fins = 6 - 24, arrow tip(height) = 40 % of arrow fin.	numerical (FEM-based) method, hot fluid in the inner pipe and cold fluid in annulus,	*Nu* and j-factor rise by 113.2 % and 124.2 %, respectively.
Ali et al. [32]	Twisted tapes of various PR,β and Re with water-titania NP as working fluids.	Numerical,TiO_2+H_2O as HTF,NPφ = 0.01 - 0.03, PR = 44 - 11, twist angles=2π - 8π, RNG k-ε solver with SIMPLE algorithm used.	*Nu* raises to 65.1 % with higher number of blades, and *f* by six times with lower PR, PEC value was increased from 6.3 – 11.8%
Syed et al.[33]	Triangular solid fin on the surface of inner tube of HX.	Lamiar, FEM solver, nubmer of fins= 4-24, crown angel=6°,fin height =0.2 - 1.	Nu rises by 1–177 times.
Vijayaragavan et al [34]	DPHE with rectangular/ triangular longitudinal cavities in the annulus to form circumferential labyrinth passages.	Experimental and 2D-Numerical, Re= 20 000 - 43 00, k-epsilon turbulence mode, Hot water in annulas, T_{hot} inlet=350°K, T_{cold} inlet=295°K	HT rate rises by incesing HT surface area and turbulence in the flow.
Eiamsa et al.[35]	louvred strip in the annulus in a forward and backward arrangement. With tube and shell diameters of 19.6 and 38 mm, respectively.Counterflow arrangement.	Experimental, Re = 6000 - 42,000, θ = 15°, 25° and 30°, Pitch= 45 mm	Nu and Δp raised by 284% and 413%, respectively, PEC=2.65 at θ=30°.
Maakoul et al.[36]	DPHE with (longitudinal) split fins on the inner tube	Numerical, laminar flow, fin pitch 0.333 and 0.166m, number of fin 24. Fin height 12.70mm	Split fins disrupt the boundary layer, and the HT of annulus fluid rises by 31%–48%.
Song et al. [37]	The perforated helical fin on the inner pipe of DPHE.	Numerical SST k-ω model used, Re = 4000 - 16,000, perforation diameters =0 - 12 mm, pitch 80mm, fin thickness= 1mm.	Nu for helical perforated fin rose by 20.2% and *f* by 11.0%
Ravikumar and Raj [38]	The counterflow arrangement with m_f is between 0.01- 0.07 kg/s, with hot, and cold water in the inner and outer tubes.	Numerical, No. of Fins = 1–10, cold fluid m_f = 0.01-0.07 kg/s, hot fluid m_f = 0.025,	Nu rose by 220%, while *Δp* by 10%

Table 3. Recent works on different types of inserts in DPHEs.			
Authors	Configuration	parameters	Result
Dhumal et al. [52]	TT is inserted in the inner tube with a helical fin on the outer surface of the inner tube of DPHE.	Experimental, Turbulent, twist ratio = 6.77 – 3.38(TT), helical tape = 1- 0.5	*Nu* rose by 315 % and *f* by 8.7 times, with a maximum TPF of 3.06.
Arjmandi et al.[53]	DPHE with a combination of VG, TT, and NP (Al_2O_3-H_2O)	Numerical, RSM, PR=0.09 - 0.18, Re = 5000-20000, , NP(ϕ=0.04), θ=0°-30°.	Nu and f rise by five times. Reducing α of VG, both *Nu* and *f* rise.
Abdulrasool et al.[54]	helical wire with perforations wounded around the inner pipe of DPHE	Numerical(SST K-ω turbulence model), m_f(cold)=0.01-0.07, m_f (hot)= 0.04 to 0.08 kg/s , wire= 48 turns × 11 (mm) pitch.	A 600% rise in *U* and a 45% rise in ξ

Heeraman et al. [55]	Counterflow DPHE with dimpled TT inserts	Experimental, dimples diameters D = 2 - 6 mm, (D/H) = 1.5 - 4.5, twist ratio= 5.5, *Re* = 6000 - 14,000	*Nu* rises, then falls with an increase in diameter from 4 to 6 mm, while *f* rises with a rise in diameter.
Sheikholeslami et al. [56]	Perforated conical ring, direct and reverse conical ring array.	Numerical, RNG k − ε model, open area ratio = 0–0.0833, Re = 6000–12,000, conical angle = 0°–30°, PR = 1.83–5.83.	*f* reduces with the rise in the open area ratio, *PR* and *Re*, while *Nu* reduces with the rise of the open area ratio and PR.
Yadav [57]	Half-length of the TT insert in DPHE of U-shape.	Experimental, counterflow, oil as HTF(m_f=4-30 L/min), Outer: cold water, at 25°C	h_m and f rose by 40% and 1.3-1.5 times, respectively.
Pradecta et al. [58]	NP (titanium dioxide) and TermoXT 32 with TT inserted in the inner pipe of DPHE.	Experimental, twist ratio = 7.35- 4.72, m_f = 12 - 20 LPM, NP Vol.% = 0 - 0.3%.	The use of NP leads to a superior HT rate; also, HT rises with the rise in v_f of NP.
Padmanabhan et al [59]	Helical wire insert of various PR on the annulus side of DPHE	Numerical(k- ε model), pitch = 5 and 15 mm, water as HTF, Cold fluid at 28 °C and hot fluid at 90 °C at constant m_f of 0.2 m/s	h_m improved by 63.91% for lower PR= 5 mm, which reduces to 31.39% with a rise in PR at 15 mm.
Pourahmad et al. [60]	DHPE with wavy strip insert of various θ.	Experimental θ= 45°-150° *Re:* 3000–13,500, Inner: hot water, Outer: cold water Counterflow	ξ rises by 71%, with *f* by 600%, the ξ rises with the rise in *Re* and declines with the rise in θ. Maximum NTU and ξ noted at θ= 45°

Table 4. Recent works on different combinations of NP and passive HT enhancement in DPHEs.

Authors	Method	Result
Chun et al. [70]	Using alumina NP in an annulus of DPHE under laminar flow.	13% rise in h_m for AK and 10% rise for AR NP.AK: alumina NP of 43 nm size with a hydrophobic surface. AR: alumina NP of 27–43 nm size with hydrophilic surface Equation: $h_i = \frac{k}{d} \times 1.7 \times \mathrm{Re}^{0.4}$
Rabienataj et al. [71]	Investigation of Al2O3-water characteristics in a DPHE under turbulent flow regime	HT rises with a rise in Re and φ of NP. 20% rise in *Nu* for the case of 1% v_f Equation: $Nu_{nf} = 1.25(\mathrm{Re}-1500)^{0.357}\,\mathrm{Pr}_f^{\,0.07}(1+2.5\Phi^{0.54})$
Wu et al. [72]	Water is a base fluid with NP in a DPHE with a helical tube under laminar and turbulent flow.	HT augmentation by 0.37% to 3.43% using different φ on NP at a constant flow rate in laminar-turbulent flows. Correlation (laminar flow): $Nu_b = 0.089 De_b^{\,0.775}\,\mathrm{Pr}_b^{\,0.4}$ $De = \mathrm{Re}\left(\frac{D_i}{D_{coil}}\right)$

Maddah et al. [73]	DPHE with modified TT inserts with working fluid (titanium dioxide NP) under turbulent flow.	There is a 40% rise in HT and a 23% rise in *f* for RGPR and NP rather than TT and NP. Correlation: $Nu = 0.056\,\mathrm{Re}^{0.72}\,\mathrm{Pr}^{0.4}(1+\pi\Phi)^{2.75}(1+\frac{\pi}{2y})^{1.1}GPR^{-0.75}$ $f = 0.375\,\mathrm{Re}^{-0.24}(1+3\pi\Phi)^{0.6}(1+\frac{\pi}{y^{1.4}})GPR^{-0.35}$
Nam et al. [74]	water/Al2O3 NP of various φ in a DPHE with helical coil tube	The 1.0 v_f NP showed a h_m, which is 1.43 times higher than water and a Nu of 1.38 times higher than water. NP's Δp was greater than water's due to the increased ρ and μ induced using NP. A relative TPF of 1.4 was noted when compared to water.
Armstrong et al. [75]	Silver (Ag)-graphene oxide (GO) hybrid NP in the annulus of DPHE. Three different molar φ of Ag ornamented GO hybrid NP.	Augmentation in h_m, Nu and TPF of 62.9%, 33.55%, and 1.29, respectively, was recorded with the 0.09 M Ag-GO hybrid NP, at *Re* of 1,451 and m_f of 47 g/s.
Kavitha et al [76]	HT agumetation of DPHE with copper oxide NP of various v_f of 0.002-0.004%.	HT increases with an increase in v_f
Somanchi et al. [77]	DPHE with TiO_2-SiC/water NP of various v_f as cold fluid of m_f (17.5 to 34.5 lpm) and constant hot fluid m_f.	The optimum NP ratio TiO_2:SiC is 1:2, giving U a value of 22.92% and f a value of 11.20 % higher when compared with base fluid.
Hozaifa et al. [78]	Al_2O_3 NP of various v_f (0.05% to 0.4%) and constant m_f was used as working fluid in the inner tube, and water was used at the constant mf on the annulus side.	h_m rises with a rise in v_f of Al_2O_3 till 0.1%, then falls. The Nu rises with Re for both the inner tube and annulus fluid.
Alhulaifi [79]	TiO_2/water NP of various v_f 0.2 - 0.6 as HT fluid under turbulent conditions with Re between 4000 - 18,000, used for nuclear reactors cooling	h_m rises with a rise in Re and v_f and temperature differences between fluids.

Table 5 Comparision between different heat transfer enhancement methods employed in DPHE							
Technique	Mechanism	Heat Transfer Enhancement	Δp Impact	Cost	Manufacturing Complexity	Thermal Stability	Applications
Extended Surfaces	Increases surface area for heat transfer	Moderate to high	Low	Low	Low	High	Heat exchangers, radiators
Turbulators/Inserts	Induces turbulence in the fluid	High	Moderate to high	Moderate	Low	Moderate	Heat exchangers, HVAC systems
Surface Roughness	Disrupts boundary layer, enhancing turbulence	Moderate	Low to moderate	Low	Low	High	Heat exchangers, condensers
Finned Tubes	Increases surface area through fins	High	Moderate	Moderate	Moderate	High	Air conditioning, automotive radiators
Nanofluids	Suspension of nanoparticles in base fluids	Very high	Moderate	Moderate to high	Moderate	High	Electronics cooling, automotive, solar collectors
Coiled Tubes	Enhances fluid flow and promotes mixing	High	Moderate	Moderate	Moderate	Moderate	Chemical reactors, heat exchangers