EMERGING APPROACHES FOR OPTIMIZING THE PERFORMANCE OF DOUBLE-PIPE HEAT EXCHANGERS

Modassir Ahmad[1], Piyush Kumar Verma[2]

[1]Research Scholar, Department of Mechanical Engineering,Corporate Institute ofScience & Technology, Bhopal

[2]Assistant Professor, Department of Mechanical Engineering,Corporate Institute ofScience & Technology, Bhopal

Abstract

Double-pipe heat exchangers (DPHEs) are a common heat exchanger design for industrial heating, cooling, heat recovery, and energy-management applications, but conventional double-pipe heat exchanger designs may not offer sufficient thermal performance. Several new design concepts for enhancing DPHE performance by geometric modifications, passive inserts, extended surfaces, and computational fluid dynamics (CFD) analysis are discussed. Analysis of the tube dimensions, annular passage, flow configuration, modified tube geometry, twisted tape, twisted fins, wire coils, vortex generators, perforated inserts and finned configuration. It has been found in published studies that these methods can improve heat transfer by increasing effective surface area, boundary layer disruption, secondary flow and mixing of the fluids. But in many cases, the pressure drop, friction factor and pumping power requirements increase with thermal enhancement. CFD can be a helpful tool to investigate these thermal-hydraulic interactions and to assess advanced designs. Overall optimization of DPHE involves the achievement of a compromise between heat-transfer enhancement, hydraulic performance, manufacturability, reliability, fouling resistance, and operating conditions.

Keywords: Double-pipe heat exchanger; Design optimization; Passive heat transfer enhancement; Thermal-hydraulic performance; Computational fluid dynamics (CFD).

I. Introduction

One of the simplest heat transfer devices is the double-pipe heat exchanger (DPHE), which has two concentric pipes through which hot and cold fluids are passed, in most cases in parallel flow or counter flow. The separating wall is used for heat transfer from the hot fluid to the cold fluid without any mixing. Because of their simplicity, low maintenance, versatility, and operating ability in a wide variety of applications, they have found application in the chemical, food, petroleum, power generation, refrigeration, HVAC, and other industrial processes[1], [2]. In applications such as heating, cooling, preheating, reheating, pasteurization and waste-heat recovery systems, efficient thermal energy recovery and utilization is essential, and this is where DPHEs can be used. A conventional smooth-tube DPHE, however, can have limited thermal performance due to the formation of thermal and hydrodynamic boundary layers especially in the case of weak fluid mixing. Thus, the need for more effective heat transfer without compromising the desired hydraulic performance is important in design consideration[3], [4].

Optimization of the design of DPHEs is therefore a challenge that must consider both the characteristics of heat transfer enhancement and also the characteristics of pressure drop. Heat transfer can be enhanced by increasing the number of transfer areas, the fluid velocity, or the turbulence[5]. This can be achieved at the expense of greater fluid friction and greater pumping costs. The tube diameter, tube length, annular gap, flow arrangement, surface geometry, and size and spacing of the enhancement elements are, therefore, important design variables. A number of design-based solutions have been studied such as twisted tape, wire coils, ring inserts, and passive, flow-disturbing elements like fins and modified tube geometries[6]. The downside of these modifications is the hydraulic penalties associated with them, but they may also offer the advantages of increased surface area, disruption of boundary layers, generation of secondary flow, and enhanced fluid mixing[7], [8]. Recent studies have also shown the application of CFD to study velocity and temperature fields, pressure distribution, heat-transfer coefficients and flow structures for various DPHE configurations. The design evaluation using CFD can thus be used to compare different geometries and enhancement arrangements in a systematic manner prior to experimental implementation, offering a valuable tool for the design of thermally effective and hydraulically acceptable DPHEs.

II. Geometric and Configuration-Based Design Optimization

One of the most basic design strategies for enhancing the performance of double-pipe heat exchangers (DPHEs) is to vary the size and the passages through which the fluids flow in order to affect the available heat-transfer area, the flow velocities, mixing, and hydraulic resistance. The design parameters for tubes should therefore be considered in conjunction with each other, and not individually: tube diameter, tube length, annular clearance, flow arrangement and geometry of the surface. It has been found that various modifications of the basic smooth-tube configuration can lead to better thermal performance, but increased heat transfer is often associated with increased pressure drop and frictional losses.[9], [10]

1. **Tube Dimensions and Annular Passage:** The hydraulic diameter, flow velocity, heat transfer area and available annular passage depend on the inner and outer tube diameters. A decrease in shell-side diameter, for instance, can lead to higher heat-transfer coefficients but also to significantly higher pressure drops. The study on the helically corrugated DPHEs revealed that both pressure drop and heat transfer are influenced by the change of the diameter of the shell, which indicated the necessity of selecting an appropriate annular clearance. Tube length also affects the available heat-transfer area and the temperature development, and hydraulic diameter affects the Reynolds number and the flow resistance. So, adequate heat transfer area should be provided without undesirable frictional losses, and dimensional selection should be aimed at this.
2. **Flow Arrangement:** DPHEs are typically either a parallel-flow or counter-flow system. Both fluids travel with parallel flow, while counter flow has fluids traveling in opposite directions. Under equivalent circumstances, counter-flow operation reports a more favorable temperature driving force and higher heat-transfer rates than do parallel flow operations. Hence, a critical design parameter for a given thermal duty for a DPHE is the flow arrangement.
3. **Modified Tube Geometry:** Helical, corrugated, wavy, curved, oval, and sinusoidal geometries are some of the modifications that can be made to the conventional circular tube to improve fluid mixing and to break up boundary layers. These changes can be used to enhance the Nusselt number and the amount of heat transfer, but most of the time they also raise the pressure drop and friction factor. Experimental and numerical studies of

corrugated tubes, for instance, have reported better heat transfer and higher hydraulic losses, where the pitch and height of corrugations have a significant influence on the performances. Recent studies also highlight the need for moderate geometric changes for a more thermal-hydraulic balance rather than just increasing surface disturbance.

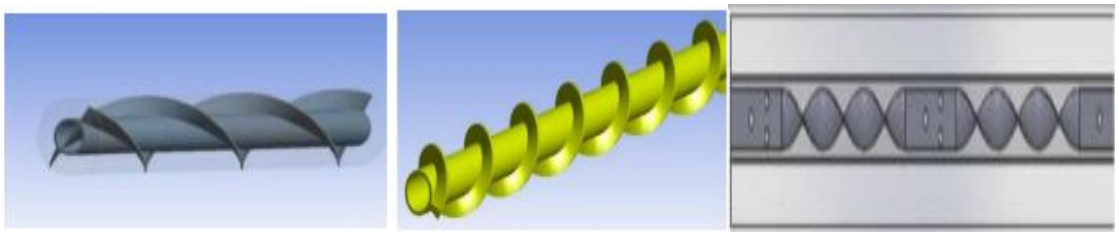
III. Passive Inserts and Extended-Surface Design

Passive enhancement is one of the effective design methods to improve the thermal performance of double-pipe heat exchanger (DPHE) without using extra external energy. The flow inside a surface is changed, the heat-transfer area is increased, and the thermal boundary layer is perturbed by the presence of inserts and extended surfaces. Twisted tape, twisted fins, wire coils, ring inserts, perforated inserts, longitudinal fins and helical fins are all common passive forms. They are very dependent upon geometry and operating conditions; the more effective the flow disturbance, the more effective the heat transfer, but the higher will be the frictional losses and pressure drop. [11][12].

1. **Twisted-tape inserts:**Twisted tapes create swirl and secondary flow that continually breaks down the thermal boundary layer and enhances fluid mixing. Some of the key parameters are twist ratio, width of tape, thickness, and pitch. The heat transfer coefficients and Nusselt numbers have been reported to increase with twisted tapes, although the corresponding increase in pressure drop should be taken into consideration. Flow disturbance can be amplified through the use of modified or cut twisted tapes, where additional mixing regions are created.
2. **Twisted-fin inserts:**Twisted fins provide more area for heat transfer and as well as deflect and generate vortices. The size, thickness, twist angle, and pitch of their fins affect the area available, the flow passage, and the strength of secondary flow. Therefore, these parameters offer direct possibilities to modify the thermal enhancement/hydraulic resistance relationship.
3. **Wire coils and ring-type inserts:**Ring inserts periodically interrupt flow and decrease boundary-layer development, and the coils in the wire promote swirling motion and enhance mixing. Geometric variables that are important are wire diameter, coil pitch, ring spacing, ring height, and the position of the insert. Non-uniformly spaced and perforated

rings have also been investigated recently with the objective of influencing the heat-transfer enhancement versus the pressure loss.

4. **Perforated and modified inserts:**By perforating, some of the fluid can go through the insert, creating more jets, mixing and local flow redistribution. Thus, flow resistance can be controlled by perforation size, number, arrangement and spacing without losing the boundary-layer disruption.
5. **Longitudinal and other extended fins:**Longitudinal and helical fins can provide more heat transfer surface and create secondary flow. The helical or split-fin arrangement gives greater flow disturbance than the conventional longitudinal fin arrangement, but may also increase friction factor; the height, thickness, pitch and spacing of the fins have a strong effect on the performance.



Twisted tape Helical fin Perforated

Figure 1: Passive Inserts and Extended-Surface Design[13]

Passive inserts and fins generally enhance the heat transfer by the mechanisms of breaking the boundary layer, increasing the heat transfer surface area, creating vortices, and producing secondary flow. These mechanisms also result in higher wall shear and flow resistance, however. Hence it may not always be more efficient to increase the Nusselt number, and the pressure drop and friction factor must also be taken into account when choosing the geometry of the inserts and the fins. More recent work involving corrugated and perforated configurations also shows that the geometric intensification can bring significant benefits in terms of thermal gains with associated hydraulic penalties.[14], [15]

IV. Challenges in Optimized Double-Pipe Heat Exchangers

While the heat transfer performance of a double pipe heat exchanger (DPHE) can be significantly enhanced by designing the exchanger geometry, incorporating fins and/or inserts, there are practical challenges associated with its implementation. One of the biggest challenges is to get an adequate amount of thermal enhancement without adding excessive hydraulic resistance, while maintaining manufacturability, durability, and reliability for the modified exchanger in real service conditions. It is noted in published reviews that heat transfer improvement is often accompanied by an increase in the friction factor and/or the pressure drop, so that thermal and hydraulic performance are not separable in the design of the DPHE.[16], [17]

1. **Thermal–hydraulic trade-off:**The heat transfer coefficient and the Nusselt number increase with increasing turbulence, secondary flow or heat transfer area, though increasing pressure drop and friction factor may also occur. So, maximising the transfer of heat alone may not result in a practically appropriate design.
2. **Pumping-power requirement:**Inserts and fins increase flow resistance and consequently require greater pumping power. This is particularly important for tightly spaced or strongly twisted configurations, where greater flow disturbance can produce substantial hydraulic losses.
3. **Manufacturing complexity:** The twisted tubes with complex geometry, including twisted fin, perforated ring, and modified twisted tape, may be more challenging to fabricate and assemble than the conventional smooth tubes. In addition to the thermal performance being predicted, feasibility must be taken into account for manufacturing processes.
4. **Fouling and blockage:**Complex insert arrangements and narrow passages can produce sites where deposits can form, which may lead to future loss of long-term heat transfer performance and reduced flow. Designs should thus ensure adequate space is available for flows and for practical maintenance access.
5. **Structural integrity:**Twisted parts, perforated inserts or thin fins shall not be subject to excessive deformation or failure under hydraulic forces or under repeated operating conditions and/or under thermal loading. Therefore, the mechanical reliability should not be compromised with increasing geometric complexity.

6. **Computational and validation requirements:**When complex inserts are involved, detailed three-dimensional CFD models need the use of proper meshing, turbulence-models and computational resources. Even though the modelling of the numerical predictions depends on modelling assumptions and boundary conditions, experimental validation is still important. DPHE recent research synergises CFD flow-field analysis, with experimental/comparative assessment to assess the reliability of enhanced configurations.
7. **Operating-condition dependence:**There is no single geometry that is applicable to every Reynolds number, flow rate, fluid, and thermal duty. For some operating conditions a configuration that works well may result in too high of a pressure drop under other conditions. Therefore design of the DPs should be based on the operating range and not just on one optimised design.

Table 1: Challenges in Optimized Double-Pipe Heat Exchangers

Challenge	Design Consideration
Heat-transfer–pressure-drop trade-off	Higher heat transfer can result in greater pressure loss
Increased pumping power	Inserts and fins increase flow resistance and pumping requirements
Manufacturing complexity	Modified fins, twisted elements, and perforated inserts can be difficult to fabricate
Fouling and blockage	Narrow or complex flow passages can promote deposit accumulation and flow restriction
Structural integrity	Thin or complex inserts and fins must withstand thermal and hydraulic loads
CFD computational cost	Complex geometries require finer meshes and greater

	computational resources
Need for experimental validation	Numerical predictions require validation under realistic operating conditions
Operating-condition dependence	A suitable geometry for one flow condition may not perform similarly under another

V. Applications of Double-Pipe Heat Exchangers

Double-pipe heat exchangers (DPHEs) are widely applied in a variety of thermal applications due to their comparatively low pressure and temperature operating limits, simplicity of construction, ease of maintenance, modularity and ease of use. Because of their tube-in-tube construction they can be used for the transfer of heat from one liquid to another liquid, or from a liquid to other process streams, where moderate heat transfer duties are required. Their application is reported in published literature for use in chemical, food, oil and gas, refrigeration, air-conditioning, power, solar-energy and other process applications. They can also be used for conventional industrial processes and for energy efficiency applications because they can also be used for heating, cooling, preheating, reheating, pasteurizing, and effluent heating.[18], [19]

1. **Industrial heating and cooling:**DPHEs are employed in process heating and cooling applications such as preheating, reheating, pasteurization, sterilization, and effluent treatment. However, they are also relatively simple to construct, and thus can be applied in small and medium-scale industrial systems.
2. **Waste-heat recovery:** DPHEs can recover thermal energy from hot exhaust or process streams and transfer it to colder fluids for preheating or other useful purposes, reducing the amount of external energy required by the process.
3. **Process, chemical and petrochemical industries:** Their ability to handle high temperatures and pressures and their straightforward maintenance make them useful for process-fluid heating and cooling in chemical, oil, gas, and petrochemical operations.
4. **Solar thermal systems:** DPHEs can be integrated into solar-water-heating and solar thermal systems to transfer energy between a solar-heated working fluid and the fluid requiring heating.

5. **HVAC and refrigeration:** They are applied for heating and cooling duties in air-conditioning and refrigeration systems, where compact tube-in-tube arrangements can provide practical heat-transfer solutions.
6. **Energy recovery systems:** Their application extends to renewable-energy and energy-recovery systems, including solar energy, geothermal systems, and other thermal-energy utilization processes where heat must be transferred between separate fluid streams.

Table 2: Applications of Double-Pipe Heat Exchangers

Application Area	Typical Thermal Application
Industrial heating and cooling	Heating, cooling, preheating, reheating, and pasteurization of process fluids
Waste-heat recovery	Recovery of heat from hot process streams for preheating colder fluids
Chemical and petrochemical industries	Heating and cooling of process fluids under high-temperature and pressure conditions
Solar thermal systems	Heat transfer between solar-heated working fluid and water or other process fluids
HVAC and refrigeration	Heating and cooling duties in air-conditioning and refrigeration systems
Energy recovery systems	Thermal-energy recovery in solar, geothermal, and other energy systems

VI. Literature review

Al-rawashdeh, (2025)[20]In this paper, a novel numerical analysis for the 2D heat exchanger (HE) model is presented. The analysis utilises computational fluid dynamics (CFD) simulations to investigate the influence of "pipe length on the efficiency and the Log Mean Temperature Difference (LMTD) of parallel and counterflow double-pipe heat exchangers", while simultaneously maintaining constant flow rates, inlet temperatures, and fluid properties. The results show that pipe length has a significant impact on heat exchanger efficiency and LMTD in both parallel and counter-flow HEs. Longer heat exchangers improve heat transfer effectiveness

by providing more time for thermal exchange, a larger heat exchange surface area, and a more uniform temperature distribution. Because of the greater temperature differential between the fluids, counterflow heat exchangers also demonstrated better efficiency than parallel flow heat exchangers at all lengths. For engineers and designers looking to optimise heat exchanger designs for industrial applications, where improving heat transfer efficiency and reducing energy losses are essential for affordable and sustainable thermal management systems, these insights are especially helpful.

Wang et al., (2024)[21]In this work, the thermo-hydraulic performance of a double-pipe heat exchanger (DPHE) for turbulent regimes employing rectangular vortex generators (RVG) and sinusoidal vortex generators (SVG) with and without holes on the annular side is examined. The numerical analysis is carried out for various VG spacings (60, 100, and 300 mm) and angles of attack (α) (15°, 45°, and 75°). With the exception of the 15° instance, the RVG cases exhibit more heat transfer than the SVG cases when comparing the heat transfer behaviour for a given α. The form with a low and mild curve increases flow velocities and vortex strength, which improves heat transfer effectiveness. Additionally, the Nusselt number of the 15° SVGs-hole case is larger than that of the no-hole case. For the 45° and 75° cases, adding holes to the VG greatly lowers the pressure drop, while it stays the same for the 15° instance. Furthermore, as compared to the smooth pipe at the Reynolds number of 5,711, the 75° RVG case produces the greatest Nusselt number among the examined examples, with an improvement of 42.4%. The 15° SVGs-hole example achieves the best performance evaluation criterion (PEC). The spacing of 60 mm yields the greatest PEC of 1.22 when the effects of various spacings are investigated. In summary, the current study offers insightful information for improving overall system performance in DPHEs and optimising VG design.

Laue et al., (2026) [22]examines the effects of passive flow changes, particularly geometrically spaced and perforated ring inserts, on heat transfer and pressure drop in a DPHE using three-dimensional Computational Fluid Dynamics (CFD) simulations. A thorough mesh independence analysis and rigorous validation against proven empirical correlations and experimental data were used to confirm the correctness of the 3D numerical model that was developed for the study. The impact of geometric spacing (G-factor) and the quantity of holes per ring was investigated in further simulations. Critical insights into the underlying processes were obtained

by analysis of both turbulent kinetic energy (TKE) and velocity vector fields, which demonstrated how ring shape and perforations disturb boundary layers and produce advantageous turbulence. Additionally, as functions of Reynolds number, G-factor, and porosity, regression-based multivariate correlations for the Nusselt number and friction factor were developed. With 96% of the correlation-predicted Nusselt numbers deviating by less than ±5% from the corresponding CFD findings and the comparable friction factor values deviating by less than ±10%, validation against the whole set of 75 CFD simulation scenarios showed remarkable accuracy.

Haw et al., (2025) [23]In order to optimise thermal-hydraulic performance, this paper investigated the incorporation of twisted fins (TF) on the interior wall of the outer pipe in a double-pipe heat exchanger (DPHE). An ideal configuration for energy efficiency is determined by analysing the effects of different twist angles within the turbulent flow regime on heat transfer and pressure drop. ANSYS Fluent simulations were carried out using the COUPLED technique to solve the Navier-Stokes equations and the SST k-ω viscous model to study the effects of whirling flows and vortex interactions caused by TF. The findings demonstrate that TF greatly improves heat transfer by enhancing fluid mixing and upsetting thermal boundary layers, but it also raises pressure drop because of increased turbulence and friction. The main mechanism for enhancing heat transfer is found to be elevated turbulent kinetic energy (TKE), which increases with increasing twist angle and is linked to swirling flows and vortices. Nevertheless, the rate of improvement in heat transfer decreases at twist angles greater than 40°, suggesting diminishing benefits. With a 15.80% rise in Nusselt number and a 14.93% increase in friction factor, the change from 30° twisted fin (TF30) to 40° twisted fin (TF40) represents the most notable overall improvement. All TF configurations obtain PEC > 1, according to performance evaluation criteria (PEC) values, suggesting that the gain in Nusselt number balances the increase in friction factor. TF40 is the best configuration for energy management since it has the highest average PEC of 1.305. These results show how well TF works to increase DPHE efficiency, underscoring its potential for use in heat exchangers in the future.

Kadhim et al., (2025)[24]investigates a variety of geometrical parameters, working fluids, and placements (in both inner and outer tubes). According to the results, wire coil inserts can raise the Nusselt number by up to 400% and achieve thermal performance factors of up to 4,

depending on the insertion technique, operating circumstances, and addition of other ways like active methods and nanofluids. Friction factors rose by two to seven times despite the improvement, emphasising the need to strike a compromise between improved heat transfer and pressure loss. In general, inner tube inserts performed better than outer tube inserts, especially at lower pitch-to-diameter ratios. With prediction errors of less than ±10%, numerical simulations utilising the SST k-ω turbulence model demonstrated good agreement with experimental data. The research finds gaps in the usage of hybrid insert applications and outer tube design, critically contrasts enhancing methodologies, and assesses computational fluid dynamics modelling approaches. This study is a useful resource for advanced heat exchanger design optimisation of insert designs and simulation techniques.

Dandoutiya& Kumar, (2023)[25]In order to estimate the Nusselt number and friction factor behaviour in a double pipe heat exchanger for W-cut twisted tape, an experimental analysis was conducted. Reynolds numbers ranging from 5500 to 16,000 were used, and the depth of W-cut to width of twisted tape ratios were 0.2, 0.4, and 0.6 in twisted tape with 10?mm width and 1?mm thickness. By changing the twist ratio to 5, 10, and 15, the effects of twist ratio are also examined. It has been discovered that utilising twisted tape inserts improves fluid mixing by creating turbulence and flow separation. Heat transfer and TPF were shown to be improved as a result of the increase in turbulent flow. Test section validation was carried out using experimental data and a predetermined correlation. For a depth of W-cut of 6 mm and a twist ratio of 5, the peak enhancement in Nusselt number and friction factor recorded at Reynolds number 5500 is 105.47% and 301%, respectively. In the same conditions, the maximum TPF and friction factor were observed. The highest TPF found in the present analysis is 1.35.

S. K. Singh et al., (2022)[13]Growing effective and efficient heat transfer equipment with characteristics of "cost-effectiveness, reduced size, and maximum usage in a wide variety of applications" under various operating conditions is always a challenging field due to the widespread need for heat transfer improvement in heat exchangers. The primary purpose of heat exchangers is to meet industrial demands for high heat dissipation. This review article focuses on improving heat transfer in double-pipe heat exchangers by using various flow shapes and taking heat transfer characteristics into account. A double-pipe heat exchanger has already been examined by several researchers using modelling and as an experimental device. In order to

construct an efficient system utilising a heat exchanger, a number of previous research are reviewed and concluded. The investigations demonstrate the importance of the Prandtl number, Reynolds number, Nusselt number, and pressure drop coefficient numbers. In order to improve heat transfer utilising a double-pipe heat exchanger, nanoparticles inside pipes are also closely examined. New results are fully validated and support the exploration of several other research projects.

VII. Discussion

In the present review, the emphasis has been placed on design oriented changes to improve the thermal and hydraulic performance of DPHEs. Geometric parameters like tube length, annular passage, flow arrangement, cross-sectional shape of tubes and corrugation are found to have a significant effect on heat-transfer behavior from the reviewed literature. Typically, counter-flow arrangements and well-designed dimensions ensure good thermal performance, and adjusting the geometry can enhance fluid mixing and disrupt the boundary-layer flow. The Nusselt number and heat transfer coefficients can be further increased by using passive inserts such as twisted tapes, twisted fins, wire coils, vortex generators and perforated rings, which create secondary flow and turbulence. The usual trade-offs, however are that these improvements tend to increase the friction factor and pressure drop. More recent studies using CFD simulations show the importance of detailed analysis of flow and temperature fields to assess these competing effects and determine appropriate configurations. Generally, attention should be paid to thermal enhancement, hydraulic penalty, manufacturability, fouling, structural reliability, and operating conditions in the design of DPHEs, rather than to maximizing heat transfer.

VIII. Conclusion

The review shows that for proper geometric modification, configuration selection and passive enhancement method, the performance of double pipe heat exchanger can be significantly improved. The pressure losses, the mixing and the fluid velocity are directly affected by the tube's dimensions, the annular clearance, the arrangement of the flow and the modified shape of the tube. Thermal enhancement opportunities to disrupt the boundary layer, break up secondary flow and increase the effective surface area are further provided by passive devices such as twisted tapes, twisted fins, coils of wire, and vortex generators, perforated rings, extended fins. But, a higher flow disturbance tends to result in higher pressure drop and pumping-power

requirements. Thus, a thermal-hydraulic approach, complemented by CFD and experimental validation is desirable for the optimized design of DPHEs. The reviewed studies also show that there is no single configuration that is universally applicable since performance is dependent on geometry, Reynolds number, fluid properties and operating conditions. The development should then focus on designs that are manufacturable, durable, and energy efficient, offering better heat transfer characteristics with minimal hydraulic penalty.

References

[1] X. Qi, J. Yang, Y. Zhang, J. Wang, and X. Guo, "Simulation study of the influence of circular arc vortex generator size on the heat transfer characteristics of fin-and-tube heat exchanger," *Sci. Rep.*, vol. 15, no. 22059, pp. 1–14, 2025, doi: 10.1038/s41598-025-05071-4.

[2] A. A. Usmani, P. Shrivastava, and S. Singh, "Impacts of Fins on The Heat Transfer Characteristics in A Shell and Cone-Shaped Coil Heat Exchanger," *Int. J. Innov. Sci. Eng. Manag.*, vol. 4, no. 1, 2025, doi: 10.69968/ijisem.2025v4i1106-117.

[3] X. Liang, M. Min, K. Bian, and J. Cheng, "Study on the enhanced heat transfer and exergy performance of the finned tube heat exchanger with vortex generator," *Int. J. Therm. Sci.*, vol. 210, p. 109639, 2025, doi: https://doi.org/10.1016/j.ijthermalsci.2024.109639.

[4] M. Islam, A. Nurizki, N. Ayish, M. M. Alam, V. Eveloy, and J. Alvarado, "Experimental investigation of heat transfer enhancement with radially arrayed delta winglets in a heat exchanger tube," *Int. Commun. Heat Mass Transf.*, vol. 167, 2025, doi: 10.1016/j.icheatmasstransfer.2025.109357.

[5] L. Liu, Z. Ni, H. Tang, H. Xu, and B. Jiang, "Heat Transfer Performance and Flow Characteristics of a Heat Exchange Tube with Isosceles Trapezoidal Winglet Longitudinal Vortex Generators," *Energies*, vol. 18, no. 1717, pp. 1–22, 2025, doi: 10.3390/en18071717.

[6] P. B. J and M. C. Karia, "A BRIEF OVERVIEW OF APPLICATION OF EXTENDED SURFACES (FINS) FOR ENHANCEMENT OF HEAT TRANSFER," *Glob. J. Eng. Sci. Res.*, vol. 6, no. 2, pp. 232–248, 2019.

[7] M. Sandeep and B. Chandra Shekar, "CFD Analysis on Performance of Double Pipe Two Pass Heat Exchanger," *IJSRD-International J. Sci. Res. Dev.*, vol. 4, no. 07, pp. 2321–0613, 2016, [Online]. Available: www.ijsrd.com

[8] M. M. Gabir and D. Alkhafaji, "Comprehensive Review on Double Pipe Heat Exchanger Techniques," *J. Phys. Conf. Ser.*, vol. 1973, 2021, doi: 10.1088/1742-6596/1973/1/012013.

[9] V. G. Rai and A. Muchrikar, "CFD analysis of double pipe counter flow heat exchanger subjected to varying cold fluid velocity in flat inner pipe," *Int. J. Eng. Dev. Res.*, vol. 9, no. 4, pp. 37–43, 2021.

[10] S. Kotian, N. Methekar, N. Jain, and P. Naik, "Heat Transfer and Fluid Flow in a Double Pipe Heat Exchanger, Part I: Experimental Investigation," *Asian Rev. Mech. Eng.*, vol. 9, no. 2, 2020.

[11] U. J. Modi, A. J. Modi, and C. Anghan, "Review on Heat Transfer Enhancement Technique In Fin & Tube Heat Exchanger," *Int. J. Res. Trends Innov.*, vol. 3, no. 2, p. 12, 2018, [Online]. Available: www.ijrti.org

[12] K. S. Rambhad, V. P. Kalbande, M. A. Kumbhalkar, V. W. Khond, and R. A. Jibhakate, "Heat Transfer and Fluid Flow Analysis for Turbulent Flow in Circular Pipe with Vortex Generator," *SN Appl. Sci.*, vol. 3, no. 7, 2021, doi: 10.1007/s42452-021-04664-8.

[13] S. K. Singh, M. K. Chauhan, and A. K. Shukla, "Heat transfer enhancement in double-pipe heat exchanger: A review," *J. Phys. Conf. Ser.*, vol. 2178, 2022, doi: 10.1088/1742-6596/2178/1/012007.

[14] R. Aridi, S. Ali, T. Lemenand, J. Faraj, and M. Khaled, "CFD analysis on the spatial effect of vortex generators in concentric tube heat exchangers – A comparative study," *Int. J. Thermofluids*, vol. 16, p. 100247, 2022, doi: 10.1016/j.ijft.2022.100247.

[15] M. El Hassan, N. Bukharin, N. Alotaibi, M. Matar, and H. H. Assoum, "CFD Study of Prism-Shaped Vortex Generators' Impact Within a Coaxial Heat Exchanger," *Math. Model. Eng. Probl.*, vol. 11, no. 10, pp. 2657–2663, 2024, doi: 10.18280/mmep.111007.

[16] J. Havlík, T. Dlouhý, and J. Krempaský, "Heat Transfer in Double Pipe Heat Exchangers with Small Tube Spacing," *J. Fluids Eng.*, vol. 147, pp. 1–10, 2025, doi: 10.1115/1.4066930.

[17] M. Lavakumar, B. V. Reddy, and K. H. Reddy, "Enhancement of Heat Transfer rate using Axially Interrupted Rectangular Fins in Double Pipe Heat Exchanger," *Int. Res. J. Multidiscip. Technovation*, vol. 6, no. 6, 2024.

[18] Y. Ding, Q. Guo, W. Guo, W. Chu, and Q. Wang, "Review of Recent Applications of Heat Pipe Heat Exchanger Use for Waste Heat Recovery," *Energies* , vol. 17, no. 11, 2024, doi: 10.3390/en17112504.

[19] M. Omidi, M. Farhadi, and M. Jafari, "A comprehensive review on double pipe heat exchangers," *Appl. Therm. Eng.*, vol. 110, pp. 1075–1090, 2017, doi: https://doi.org/10.1016/j.applthermaleng.2016.09.027.

[20] S. A. Al-rawashdeh, "CFD Analysis of Heat Exchanger Effectiveness and LMTD with Varying Pipe Length," *Emerg. Sci. J.*, vol. 9, no. 4, 2025.

[21] Y. Wang, J. J. Foo, M. V. Tran, S. R. Nair, and C. S. Oon, "Numerical investigation of thermo-hydraulic performance of perforated rectangular and sinusoidal vortex generators in a double-pipe heat exchanger," *J. Therm. Anal. Calorim.*, vol. 149, pp. 11137–11154, 2024, doi: 10.1007/s10973-023-12838-2.

[22] L. K. Laue, J. Hattel, and A. Mostafazade Abolmaali, "CFD investigation of thermo-hydraulic performance enhancement in a double-pipe heat exchanger using non-uniformly spaced perforated ring inserts," *Energy Convers. Manag.*, vol. 355, p. 121293, 2026, doi: 10.1016/j.enconman.2026.121293.

[23] W. Haw, C. S. Oon, and E. Von Lau, "Thermal-Hydraulic and Hydrodynamic Analysis of Twisted Fins in a Double-Pipe Heat Exchanger Willy," *Results Eng.*, vol. 26, no. March, 2025, doi: 10.1016/j.rineng.2025.104642.

[24] S. A. Kadhim *et al.*, "Enhancing the thermal performance of double-pipe heat exchangers using wire coil inserts: A focused review," *Sci. African*, vol. 29, p. e02896, 2025, doi: 10.1016/j.sciaf.2025.e02896.

[25] B. K. Dandoutiya and A. Kumar, “Study of thermal performance of double pipe heat exchanger using W-cut twisted tape,” *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 45, no. 2, pp. 5221–5238, Jun. 2023, doi: 10.1080/15567036.2023.2207497.