Numerical Study on Fluid Flow and Heat Transfer in Twisted Ducts: A Review

Bhuvaneshwari Yadav Killadi
Dept. of Mechanical Engg.,
NIT Nagaland,
Chumoukedima, Nagaland, India
0009-0002-7823-7131

Avnish Kumar
Dept. of Mechanical Engg.,
NIT Nagaland,
Chumoukedima, Nagaland, India
0009-0003-6084-9700

Himavantha Sri Raghava Naga Sai Chebolu
Dept. of Mechanical Engg.,
NIT Nagaland,
Chumoukedima, Nagaland, India
0009-0005-6470-3156

Amit Kumar Singh*
Dept. of Mechanical Engg.,
NIT Nagaland,
Chumoukedima, Nagaland, India
0000-0002-3259-5067

Aditya Kumar Mishra
Dept. of Mechanical Engg.,
NIT Nagaland,
Chumoukedima, Nagaland, India
0000-0002-9756-8609

Shambhu Kumar Mahato
Dept. of Mechanical Engg.,
NIT Nagaland,
Chumoukedima, Nagaland, India
0000-0002-3118-6624

***Abstract*— Heat transfer is an extensive concept, that has various applications in many different fields of engineering. Heat transfer enhancement is being studied to improve the effectiveness of heat transfer. This review summarizes the types of ways, researchers studied to improve heat transfer by using twisted ducts of different cross-sections with the help of different numerical methods/schemes. Twisted ducts not only provide swirl flow to the laminar flow but also provide secondary flow which causes the fluid to switch from laminar to the turbulent regime for better temperature distribution and other parameters. PEC (Performance evaluation factor) solves and compare the performances of different heat exchangers of different cross-sections based on various factors including friction factor, pressure drop and efficiency. By studying heat transfer enhancement in twisted ducts with various cross-sections we get to decide which geometry provides the best heat transfer. The study is made on a various of geometry, but only certain cross-sections are emphasized, and extensive study should be done on other cross-sections as well to generate progress and improve the quality of heat transfer.**

Keywords—Twisted ducts, FVM analysis, FEM analysis, FDM analysis, PEC.

I. Introduction

Heat exchangers are one of the components of different systems or machine that are used for heating or cooling purposes according to the requirement [1]. When heating is the requirement, the heat exchanger transfer heat from hot to cold fluid to increase the temperature of the cold fluid and this extracted heat energy can be used as recycled heat energy in different industries. Contrarily when cooling is requirement, same methodology as heating is used but primary objective differs such as air conditioners. Heat exchangers are extensively employed in many different industries such as automobile industry, chemical and petrochemical industry, aerospace industry, etc.

Heat transfer enhancement by using passive methods such as twisted ducts, twisted tapes, etc of different cross-sections [2], [3]. The reason for using these twisted models is to induce turbulent, swirl and secondary flow. As much as the geometry of the heat exchanger influences the heat transfer enhancement, fluid flow and types of fluid also plays a vital role in the enhancement. (Fluid flow like, Laminar flow, turbulent flow, steady flow, unsteady flow, etc.). Twisted ducts are preferred more than twisted tapes, because of more flow area which is restricted in twisted tape due to the additional tape present in the straight, smooth duct [2], [3]. Various researchers worked on the improvement of heat transfer using twisted ducts using different cross-section.

A. Motivation:

The present review focuses on the heat transfer enhancement by using passive methods, mainly on twisted ducts of different cross-sections. It also reviews all different types of numerical methods that have been used previously by different researchers on heat transfer domain for twisted ducts. The primary goal of the researchers was to figure out which geometrical shape of heat exchanger duct can give high PEC (Performance evaluation criteria) and heat transfer enhancement. Several studies were made on certain geometric cross-sections such as elliptical, oval, etc. There is limited study on other cross-sections such as square, hexagonal, etc. Research on other cross-sectional twisted ducts either by increasing or decreasing the sides of the duct should also considered be done to improve and gain knowledge on them.

B. Flow of events:

The study in this paper is done in sequential order. Segment 2 summarizes about the numerical methods used in the problem solving the governing equations, different types of numerical methods used by the researchers referred in this review. While, twisted ducts are explained in Segment 3, different cross-sections of twisted ducts are also explored in this segment. In segment 4, Summary of this review article is written in detail. Segment 5 offers the conclusion of the paper.

II. NUMERICAL METHODS

Numerical methods are type of methods used to replicate experimental conditions and use mathematical models to simulate any particular problem that is too complex to be solved and also to use large range of fluids to be compared with experimental results [2]. Numerical methods are used in different streams or majors such as, engineering, medical, architecture, etc. Numerical methods are very significant on their own field which includes solving complex model, obtaining approximate results, it allows the researchers to predict the outcome while simulating certain conditions without going through the exacting experiments, it also gives accurate error analysis of the approximate results, above all the most important significant is that numerical methods is cost effective. Compared to experimental, which requires a great deal of set-up and time, Numerical methods is much more effective. [4]

There are various types of Numerical methods through which problems can be solved. There are different categories of Numerical methods but this review mainly focuses on Numerical methods using PDEs (Partial Differential Equations), such as, FVM, FEM and FDM, etc [1], [5]

A. Finite Volume Method (FVM)

Finite volume method is a type of Numerical methods which uses PDEs (Partial Differential Equations). FVM is broadly used in CFD (Computational Fluid Dynamics) because of its extensive use of conservation laws such as energy, mass, momentum, etc as given in Equation. (1), (2), (3) [1]. It also has conserved the fluxes and also computed which is a very important aspect of FVM.

FVM handles all sorts of complex geometries. It is used in several fields of engineering for example thermal, fluid mechanics, heat and mass transfer, etc. FVM discretizes various models such as turbulent models such as RNG k- ε model [2], [3], [7] - [11]; [11] states due to its characteristic of handling flow of fluid with high streamline curvature and in near-walls region, [12] used low Reynolds k- ε model to result in the wall molecular weight and to study flow and thermal performances and [13], [14] used realizable k- ε model to evaluate the turbulent thermal-fluid flow and [15] worked on Shear stress transport (SST) k- ω because of its high precision of results in Nusselt number & friction factor, [4], [5], [16] used SST k- ε model.

Continuity equation:

$$\frac{\partial}{\partial \chi_i}\left(\rho u_i \right) = 0 \tag{1}$$

Momentum equation:

ISBN : 978-81-978522-2-0

$$\frac{\partial(\rho u_i u_j)}{\partial \chi_j} = -\frac{\partial p}{\partial \chi_i} + \frac{\partial}{\partial \chi_j}\left[\mu\left(\frac{\partial u_i}{\partial \chi_j} + \frac{\partial u_j}{\partial \chi_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial \chi_k}\right)\right] + \frac{\partial}{\partial \chi_j}\left(-\rho\overline{u'_i u'_j}\right) \quad (2)$$

Energy equation:

$$\frac{\partial}{\partial \chi_i}\left[u_i(\rho E + p)\right] = \frac{\partial}{\partial \chi_j}\left(k_{eff}\frac{\partial T}{\partial \chi_j}\right), \ E = h - \frac{p}{\rho} + \frac{u^2}{2} \quad (3)$$

There are different types of FVM schemes: QUICK (Quadratic Upstream Interpolation for Convective Kinematics) algorithm is used in [1], [18]; SIMPLE (Semi Implicit Method for Pressure-Linked Equations) is incorporated in [2] - [5], [7], [10], [14], [15], [19] - [21]; SIMPLEC (SIMPLE Consistent) scheme is used in [11], [16], [21]. Navier-Stokes equations in cartesian form is noted as:

B. Finite Element Method (FEM)

Finite element method is a discretization that is mainly used for structural domain but it can also be used in many domains such as fluids or thermal or CFD (Computational Fluid Dynamics). [22] worked on the heat transfer improvement in a circular tube utilizing FEA

C. Finite Difference Method (FDM)

FDM is a discretization method used to solve differential equations and PDEs (Partial differential equations). It is simple, efficient and solves complex geometries. [23] incorporated FDM to solve the required parameters.

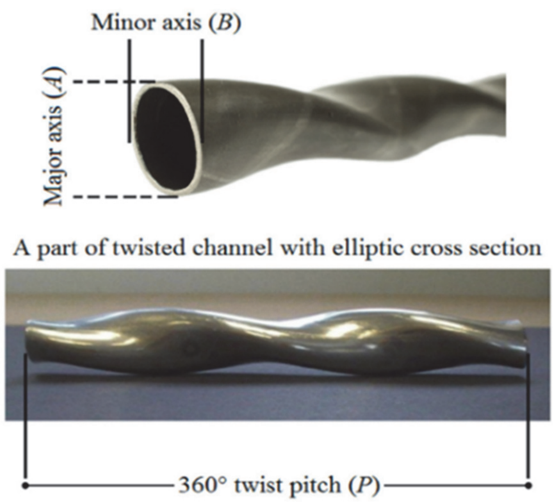


Fig.1 Twisted elliptical duct/channel [20]. Reproduced with the permission from Elsevier

III. TWISTED DUCTS

Twisted ducts are passive technique of heat enhancement technique, which are used in Heat exchangers for [2], [3] enhancing heat transfer by producing secondary flow and induce swirl flow which results in uniform temperature distribution. There are different types of twisted ducts – Twisted elliptical duct, twisted oval duct, twisted square duct, twisted hexagonal duct;

A. Twisted Elliptical duct (TET)

Twisted elliptical duct heat exchangers is studied by various researchers due of their advantages such as high heat transfer efficiency, small size, anti- vibration, self-supporting without baffles and reduced pressure drops.[11], [15], [16], [18]. Twisted elliptical duct/channel [20] is represented in Fig.1.

B. Twisted Oval duct (TOT)

Twisted oval duct or tube is a type of geometry which is utilized to enhance the heat transfer. Fig.2 represents the mesh generation of cross-section of twisted oval duct in simulation [5]. The fluid rotational motion caused by TOT leads to phenomenon of secondary and swirl flow which disrupts the boundary condition and temperature distribution [5]. [6] found that twisted tube with oval cross-section enhances the heat transfer while increasing the pressure drop. [9], [10] investigated the aspects of improving heat transfer by using oval cross-section.

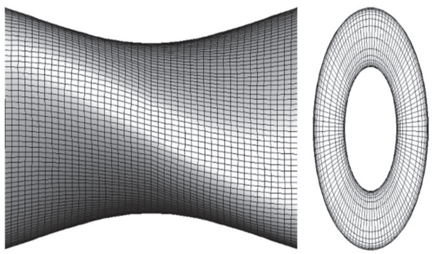
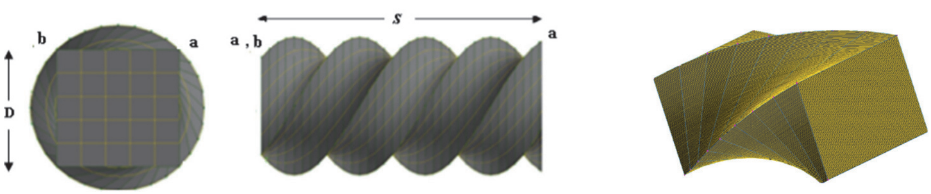


Fig.2 Mesh generation of cross-section of twisted oval duct [5].
Reproduced with the permission from Elsevier

C. Twisted Square duct (TSD)

Similar to elliptical and oval cross-section twisted ducts, twisted square duct's main objective is to enhance the heat transfer enhancement and get the best of PEC (Performance evaluation criteria). Contrasting to others, twisted square duct creates unique flow path which creates its own swirl and secondary flow. [2], [3], [7], [8]. Fig 3. shows Twisted square duct (a) for numerical analysis; (b) Computational mesh [3].



(a) (b)

Fig.3 Twisted square duct (a) for numerical analysis; (b) Computational mesh [3]. Reproduced with the permission from Elsevier

D. Twisted Hexagonal duct

Twisted hexagonal duct is a duct of hexagonal cross-section with six sides, with twists of required pitch and twist ratio, [7] compared twisted duct of square and hexagonal cross-sections and found that Nusselt number for laminar flow is high in hexagonal duct. Similar to other cross-section, it's main purpose to enhance the heat transfer rate.

IV. Summary

The Heat transfer enhancement is dependent on fluid flow and geometry of the duct, which can be used in an ideal way. It can be achieved by making use of various numerical methods that are applied on fluid flow and geometry of the duct. Numerical methods such as FEM, FVM and FDM can be used to solve PDEs. $k - \varepsilon$ & $k - \omega$ models are mostly solved by FVM so almost every researcher studying in this domain used FVM. The main objective was to find out which cross-section of twisted duct gives maximum efficiency, pressure drop and friction factor under PEC. Study is mostly done on laminar and turbulent fluid flow and its transition i.e. from laminar to turbulent after considering certain Reynolds number range. Few researchers worked on the types of fluids as well to check their compatibility with the objective and attain high capacity of the heat transfer.

V. Conclusion

The review highlights the main role of twisted ducts with various cross-sections in enhancing heat transfer in the heat exchangers. The developed swirl and secondary flows cause the fluid flow to change from laminar to turbulent flow, which improves temperature distribution across the walls of twisted duct and efficiency of heat transfer. While numerous geometrical cross-sections have been studied, the attention on certain cross-sections leads us to that further research of alternative cross-sectional shapes could give us additional advancement in heat transfer performance. Continued research is essential to upgrading heat exchanger designs and achieving better efficiency in heat and mass systems over various engineering applications.

References

[1] S. Eiamsa-ard, K. Kiatkittipong, and W. Jedsadaratanachai, "Heat transfer enhancement of TiO2/water nanofluid in a heat exchanger tube equipped with overlapped dual twisted-tapes," Engineering Science and Technology, an International Journal, vol. 18, no. 3, pp. 336–350, Sep. 2015, doi: 10.1016/j.jestch.2015.01.008.

[2] R. Bhadouriya, A. Agrawal, and S. V. Prabhu, "Experimental and numerical study of fluid flow and heat transfer in an annulus of inner twisted square duct and outer circular pipe," International Journal of Thermal Sciences, vol. 94, pp. 96–109, 2015, doi: 10.1016/j.ijthermalsci.2015.02.019.

[3] R. Bhadouriya, A. Agrawal, and S. V. Prabhu, "Experimental and numerical study of fluid flow and heat transfer in a twisted square duct," Int J Heat Mass Transf, vol. 82, pp. 143–158, 2015, doi: 10.1016/j.ijheatmasstransfer.2014.11.054.

[4] X. Tang, X. Dai, and D. Zhu, "Experimental and numerical investigation of convective heat transfer and fluid flow in twisted spiral tube," Int J Heat Mass Transf, vol. 90, pp. 523–541, 2015, doi: 10.1016/j.ijheatmasstransfer.2015.06.068.

[5] X. Li, L. Wang, R. Feng, Z. Wang, S. Liu, and D. Zhu, "Study on shell side heat transport enhancement of double tube heat exchangers by twisted oval tubes," International Communications in Heat and Mass Transfer, vol. 124, May 2021, doi: 10.1016/j.icheatmasstransfer.2021.105273.

[6] S. W. Chang, P. S. Wu, W. L. Cai, and J. H. Liu, "Turbulent flow and heat transfer of helical coils with twisted section," Appl Therm Eng, vol. 180, Nov. 2020, doi: 10.1016/j.applthermaleng.2020.115919.

[7] S. Kumar Mahato et al., "Numerical Analysis of Heat Transfer and Fluid Flow through Twisted Hexagonal and Square Duct and their Comparisons," Chem Eng Trans, vol. 71, 2018, doi: 10.3303/CET1871226.

[8] S. K. Mahato, S. C. Rana, R. N. Barman, and S. Goswami, "Numerical analysis of heat transfer and fluid flow through the twisted square duct (TSD): Nanofluid as working fluid," Journal of Mechanical Science and Technology, vol. 33, no. 11, pp. 5507–5514, Nov. 2019, doi: 10.1007/s12206-019-1043-1.

[9] C. Luo and K. W. Song, "Thermal performance enhancement of a double-tube heat exchanger with novel twisted annulus formed by counter-twisted oval tubes," International Journal of Thermal Sciences, vol. 164, Jun. 2021, doi: 10.1016/j.ijthermalsci.2021.106892.

[10] C. Luo, K. W. Song, and T. Tagawa, "Heat transfer enhancement of a double pipe heat exchanger by Co-Twisting oval pipes with unequal twist pitches," Case Studies in Thermal Engineering, vol. 28, Dec. 2021, doi: 10.1016/j.csite.2021.101411.

[11] H. Gu, Y. Chen, J. Wu, and B. Sunden, "Performance investigation on twisted elliptical tube heat exchangers with coupling-vortex square tube layout," Int J Heat Mass Transf, vol. 151, Apr. 2020, doi: 10.1016/j.ijheatmasstransfer.2020.119473.

[12] J. Cheng, Z. Qian, Q. Wang, C. Fei, and W. Huang, "Numerical study of heat transfer and flow characteristic of twisted tube with different cross section shapes," Heat and Mass Transfer/Waerme- und Stoffuebertragung, vol. 55, no. 3, pp. 823–844, Mar. 2019, doi: 10.1007/s00231-018-2471-7.

[13] H. R. Kim, S. Kim, M. Kim, S. H. Park, J. K. Min, and M. Y. Ha, "Numerical study of fluid flow and convective heat transfer characteristics in a twisted elliptic tube," Journal of Mechanical Science and Technology, vol. 30, no. 2, pp. 719–732, Feb. 2016, doi: 10.1007/s12206-016-0127-4.

[14] V. Ghazanfari, A. Taheri, Y. Amini, and F. Mansourzade, “Enhancing heat transfer in a heat exchanger: CFD study of twisted tube and nanofluid (Al2O3, Cu, CuO, and TiO2) effects,” Case Studies in Thermal Engineering, vol. 53, Jan. 2024, doi: 10.1016/j.csite.2023.103864.
[15] M. Talebi and F. Lalgani, “Assessment of thermal behavior of variable step twist in the elliptical spiral tube heat exchanger,” International Journal of Thermal Sciences, vol. 170, p. 107126, Dec. 2021, doi: 10.1016/j.ijthermalsci.2021.107126.
[16] S. M. Alempour, A. A. Abbasian Arani, and M. M. Najafizadeh, “Numerical investigation of nanofluid flow characteristics and heat transfer inside a twisted tube with elliptic cross section,” J Therm Anal Calorim, vol. 140, no. 3, pp. 1237–1257, May 2020, doi: 10.1007/s10973-020-09337-z.
[18] Y.-Q. Song, N. Izadpanahi, M. A. Fazilati, Y.-P. Lv, and D. Toghraie, “Numerical analysis of flow and heat transfer in an elliptical duct fitted with two rotating twisted tapes,” International Communications in Heat and Mass Transfer, vol. 125, p. 105328, 2021, doi: 10.1016/j.icheatmasstransfer.2021.105328.
[19] A. N. Guo and L. B. Wang, “Parametrization of secondary flow intensity for laminar forced convection in twisted elliptical tube and derivation of loss coefficient and Nusselt number correlations by numerical analysis,” International Journal of Thermal Sciences, vol. 155, Sep. 2020, doi: 10.1016/j.ijthermalsci.2020.106425.
[20] M. Khoshvaght-Aliabadi and Z. Arani-Lahtari, “Forced convection in twisted minichannel (TMC) with different cross section shapes: A numerical study,” Appl Therm Eng, vol. 93, pp. 101–112, Jan. 2016, doi: 10.1016/j.applthermaleng.2015.09.010.
[21] A. R. Sajadi, S. Yamani Douzi Sorkhabi, D. Ashtiani, and F. Kowsari, “Experimental and numerical study on heat transfer and flow resistance of oil flow in alternating elliptical axis tubes,” Int J Heat Mass Transf, vol. 77, pp. 124–130, 2014, doi: 10.1016/j.ijheatmasstransfer.2014.05.014.
[22] S. Hossain, U. K. Deb, and K. A. Rahman, “The enhancement of heat transfer in a circular tube with insert and without insert by using the finite element method,” in Procedia Engineering, Elsevier Ltd, 2015, pp. 81–88. doi: 10.1016/j.proeng.2015.05.010.
[23] K.-S. Chang, J.-S. Choi, and J.-S. Kim, “LAMINAR FLUID FLOW IN A TWISTED ELLIPTIC TUBE,” 1988.