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Research Article

Thermal Performance of Twisted Heated Duct for Different Twisting Angles

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ABSTRACT

In recent years, the focus of research is mainly on the twisted pipe and ducts, as it can significantly improve heat transfer characteristics of thermal exchangers in compact and highly effective heating systems. The conducted research seeks the impact of different twisting angles (90°, 180° and 360°) on surface temperature and Nusselt number, which allow describing effectiveness of heat transfer by convection. The analysis reveals that twisted ducts generate the secondary flows that displace the thermal boundary layer and result in higher heat transfer rates. Even 90° of twisting offer an impressive enhancement when compared to plain ducts, while 180° and 360° of twisting lead to the best results.

1. INTRODUCTION

The increasing demand for improved heat exchangers performance and enhanced energy efficiency in several processes has encouraged the investigation of twisted pipes and ducts. It is known that the twisted geometries are capable of producing secondary flows and breaking of thermal boundary layers, thus promoting better convective heat transfer and enhanced system efficiency. In this context, the state of the art of the available literature related to these twisted devices is addressed here from experimental, numerical and theoretical approaches [1-3].

The basic knowledge about the flow dynamics of twisted geometries was developed starting from recognition of the Dean number by Dean [4] . The Dean number was a dimensionless value used to describe the secondary flow phenomena in curved and twisted pipes. Readers were introduced to this measure and its implications to revealing the mixing and turbulence improvement of twisted setups. Finally, Taylor's [5] presented a deep study of their stability and consequent effects on the turbulence behavior related to their heat transfer features.

To this end, available experimental studies are important in determining the heat transfer and pressure drop characteristics of twisted pipes. In the 1980s, Bergles et al [6] performed systematic experiments to evaluate heat transfer coefficient and pressure drops present in helically twisted tubes. The results showed beneficial increase in heat transfers at the expense of additional energy required to pump. Webb and Kim [7] performed heat exchange analyses based on surface modifications and results of geometric parameters such as the pitch length and twist angle while establishing the balance between heat transfer enhancement and pressure loss. A more recent research work conducted by Wang et al. [8] focused on the influences of nanofluid flow along a twisted pipe system and identified a multiplicative influence in heat transfer improvements in light of synergistically additive effects of twisted geometry and improved thermal conductivity. Singh et al.[9] performed similar works on twisted pipes incorporating the use of hybrid nanofluids and also reported heat transfer improvement under specified conditions.

For the purpose of numerical simulations, CFD-based methods to study flow and thermal fields inside twisted pipes and ducts have flourished. Xie et al. [10] performed a CFD study on laminar and turbulent flows in twisted ducts and created numerical models for them. The models demonstrated the strong influence of geometric parameters on the heat transfer performance, helping to design the best-fit models for various applications. Gupta and Kumar [11] built upon this research to investigate the non-Newtonian models in twisted pipes and their unique flow properties and heat transfer dynamics. Li et al. [12] presented a machine learning-assisted CFD-based model for twisted pipes for performance predictions of

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different pipe characteristics. Resulting models proved to be time-efficient and accurate. Zhang et al. [13] conducted a two-phase (oil-gas) flow analysis in twisted ducts. The study highlights potential research and development applications in oil-gas separators.

Also, many studies were conducted in recent years on the twisted optimization. Ali et al.[14] studied compact exchangers with twisted pipes' performance and suggested optimum twisting ratios which would lead to a minimum pressure drop with maximum heat exchange. Zhang et al. [15] applied experimental and numerical approaches to achieve the design for bio-inspired twisted ducts, which received the inspiration from the biological systems such as blood vessels. Huang et al. [16] introduced the adaptive twisting geometry that could be changed according to the flow conditions in order to improve the performance and minimize process expenses.

The existing literature has also examined the use of twisted pipes and ducts in various industrial applications. Twisted ducts and pipes are frequently employed in heat exchangers such as condensers, evaporators, and energy recovery systems to optimize energy recovery and heat transfer during phase-change processes. The work undertaken by Patankar et al. [17] on twisted pipes as regenerative heat exchangers reported promising efficiency improvements in several applications designed for recovering waste heat. Similarly, Wang et al. [18] worked on twisted ducts employed in HVAC systems and acknowledged their benefits in improving heat exchange in compact heat exchangers. Recently, Liu et al. [19] examined twisted configurations in renewable energy systems (e.g., solar thermal collectors) and reported performance improvements in thermal absorption and distribution. Another study by Al-Dulaimi et al. [20]numerically investigated heat transfer enhancement inside a square duct using rectangular vortex generators (VGs). Although not directly involving twisted tubes, their findings are relevant. They reported that VGs positively influence heat transfer by increasing turbulence levels, with enhancements up to 40%. The heat transfer increased with the blocking ratio and the number of VGs, with a 45° attack angle producing the highest enhancement. These insights could inform future designs incorporating twisted geometries and VGs for improved heat transfer.

The present work is intended to study the heat transfer and hydraulics characteristics of twisted ducts for with different angles of twisting (90°, 180°, and 360°). The work also intends to deliver the coupled effect of twisting angle on Nusselt number, and surface temperature uniformity through the aid of enhanced computational fluid dynamics (CFD) simulations.

2.NUMERICAL SIMULATION

The numerical simulations using commercial software ANSYS-FLUENT to examine the effect of the air duct twisting on the heat transfer with the flowing air. The numerical is conducted for constant Reynolds number of 5000 under steady state conditions.

2.1 Geometry

The flow domain geometry has been constructed using SolidWorks. The computational domain has three sections, each with a square cross-section of 40x40 cm². The first zone is the entry region, measuring 50 cm (1.359 D_hRe) to guarantee fully established flow [21]. The second zone is the test section, measuring 40 cm in length. The test section is tested for two configurations including plain and twisted. The effect of twisting is investigated for three twisting angles of : 90°, 180° , and 360°. The third zone is the exhaust region, which links the test region with the ambient environment. It measures 20 cm in length. This area delineates the test zone from the influences of the environment. Figure 1 displays the physical domain.

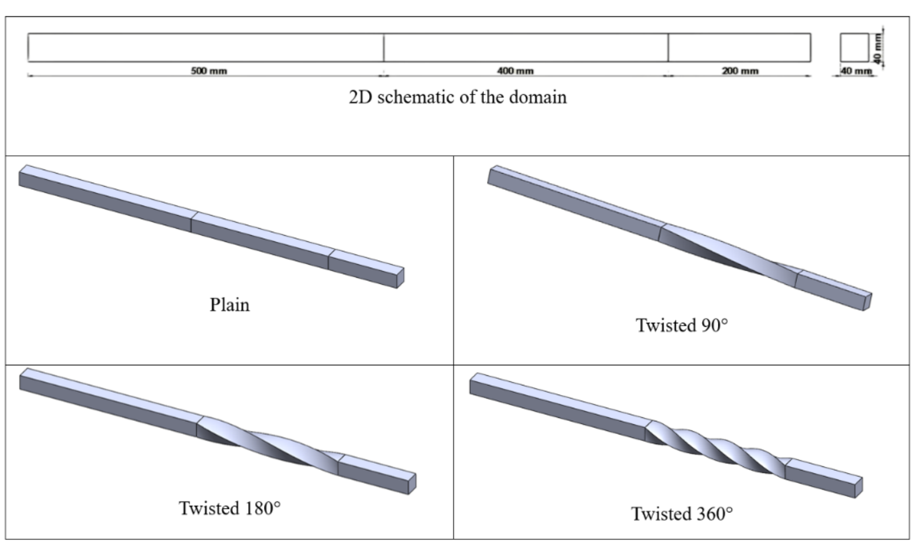

Fig.1.The physical domain

2.2 Mesh Creation

The flow domain is segmented into small elements, and the governing equations for these elements are solved, leading to the creation of a computational grid or mesh. Structured and unstructured meshing are the two categories of volume meshing techniques utilized [22]. Due to the uniform section of the entry and exhaust sections, structured hexagonal meshing is utilized for meshing them. Due to the non-uniformity of the test zone caused by the twisting, unstructured tetrahedral meshing is utilized. Also, an inflation created near the walls of the test section to precisely capture the effect of the wall on the flow. The dimensions of the components significantly influence the simulation outcomes; however, in this investigation, the element size is pertinent just in the test region due to its relation to fluid dynamics and thermal transfer. Figure 2 displays the meshed domain for twisting angle of 360°. Table (I) presents the influence of element number on the average Nusselt number within the test section. When the average Nusselt number stabilizes with variations in grid size, 1,211,864 was selected as the grid size.

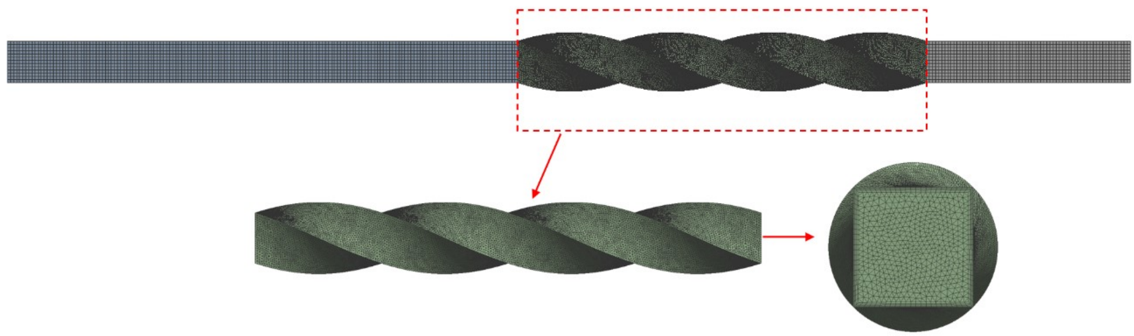

Fig.2.The meshed domain

TABLE (I): VARIATION OF AVERAGE NUSSELT NUMBER WITH ELEMENTS NUMBER.

Elements number	Nu_{av}
428,524	38.5
634,218	39.3
950,859	40.67
1,211,864	40.83
1,458,524	40.83

2.3 Governing Equations

The Navier-Stokes equations, expressed in tensor notation, decompose variables into mean and fluctuation components through Reynolds averaging. This process resembles velocity decomposition [22]:

$$u_i = \bar{u}_i + u_i' \quad (1)$$

Where $\boldsymbol{u_i}$ is the instantaneous fluid velocity, $\boldsymbol{u_i'}$ is the velocity fluctuation and $\boldsymbol{\bar{u}_i}$ is the time-averaged value of $\boldsymbol{u_i}$ at a point. The governing equations include: continuity, momentum and energy.

- Continuity Equation

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial x} + \frac{\partial \rho w}{\partial x} = 0 \quad (2)$$

The above equation may be expressed as follows, given that the mass density of fluid remains constant:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial x} + \frac{\partial w}{\partial x} = 0 \quad (3)$$

Then, the continuity equation is stated as:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (4)$$

- Momentum Equation

$$\rho \frac{\partial u_i u_j}{x_j} = -\frac{\partial P}{\partial x_i} + \mu \frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \rho \frac{\partial}{\partial x_j}\left(-\overline{u_i' u_j'}\right) \quad (5)$$

- Energy Equation

$$\rho c_p \frac{\partial u_i T}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\lambda \ \frac{\partial T}{\partial x_i} - \rho \overline{u_i' T'}\right) \tag{6}$$

Where λ **:** is thermal conductivity

2.4 Boundary Conditions

The Governing equations are solved by utilizing the following boundary conditions as in Figure (3):

- Left edge: velocity inlet
- Right edge: pressure outlet.
- Test section: heat flux

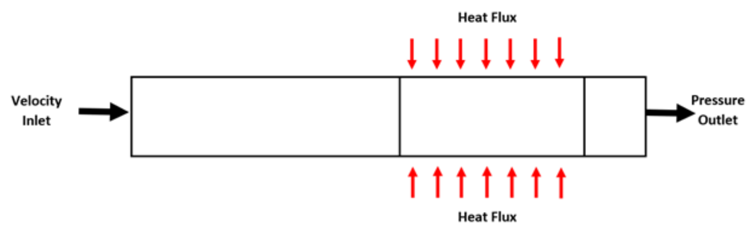

Fig. 3. The Boundary conditions

2.5 Solution

In order to perform numerical simulations of the natural convection inside the annulus and between the glass cover and the surroundings, the ANSYS Fluent set-up, in detail described below, was chosen according to ANSYS recommendation [23]. The spatial discretization settings used for numerical simulations are the second order for all equations. The convergence criteria are set to 10^{-5} for all equations.

3. RESULTS

3.1 Effect of Twisting Angle on Temperature

Figure (4) shows the surface temperature contours for the plains and twisted test sections. In the plain duct, heat transfer is limited by the relatively uniform laminar flow. The thermal boundary layer near the duct walls remains largely intact, leading to higher surface temperatures and less effective cooling or heat dissipation. This lack of mixing results in a suboptimal temperature gradient. The secondary flow induced by a 90° twist is mild. The secondary flow facilitates further mixing of the duct's wall and core regions, thus improving the heat transfer. The thermal boundary layer is also disturbed, leading to a more uniform surface temperature distribution when compared with the plain duct. This twist angle demonstrates that even a small geometric modification can provide a measurable improvement in surface temperature regulation. At higher angles, secondary flows also become stronger at 180° and 360° twisting, resulting in additional turbulence and mixing. Furthermore, the mixing effect leads to the further reduction of thermal boundary layer thickness, which consequently increases heat transfer from the fluid to the duct wall. At these higher twist angles, the surface temperature becomes even more uniform, as the flow continually refreshes the fluid near the walls with cooler fluid from the core.

3.2 Effect of Twisting Angle on Nusselt Number

The case without any enhancement of the plain duct provides a baseline with the lowest Nusselt number, where the secondary flow does not exist. In this case, convection heat transfer is not very effective, and the conductive heat transfer along the wall governs the performance.

The plain duct has lower Nusselt number than the 90° twisted duct. This means that secondary flows can be established with relatively small twist angles to promote better convection heat transfer. The dominance of the latter effect is the result of improved blending of the fluid which increases the wall heat transfer coefficient.

Then, if the twist angle is increased to 180°, it also increases the Nusselt number. Secondaries flows are intensified as a result of the increase in the angle, also twisting. This causes more agitation and better transportation of energy from the wall to the bulk fluid, increasing heat transfer at the surface and decreasing surface temperatures.

For heat transfer enhancement, the configuration with 360° twisted duct gives the highest Nusselt number indicating the superior result. The fully developed secondary flows and turbulence at this angle disrupt the thermal boundary layer most effectively leading to enhanced heat transfer, Figure (5) shows the Nusselt number for different configurations.

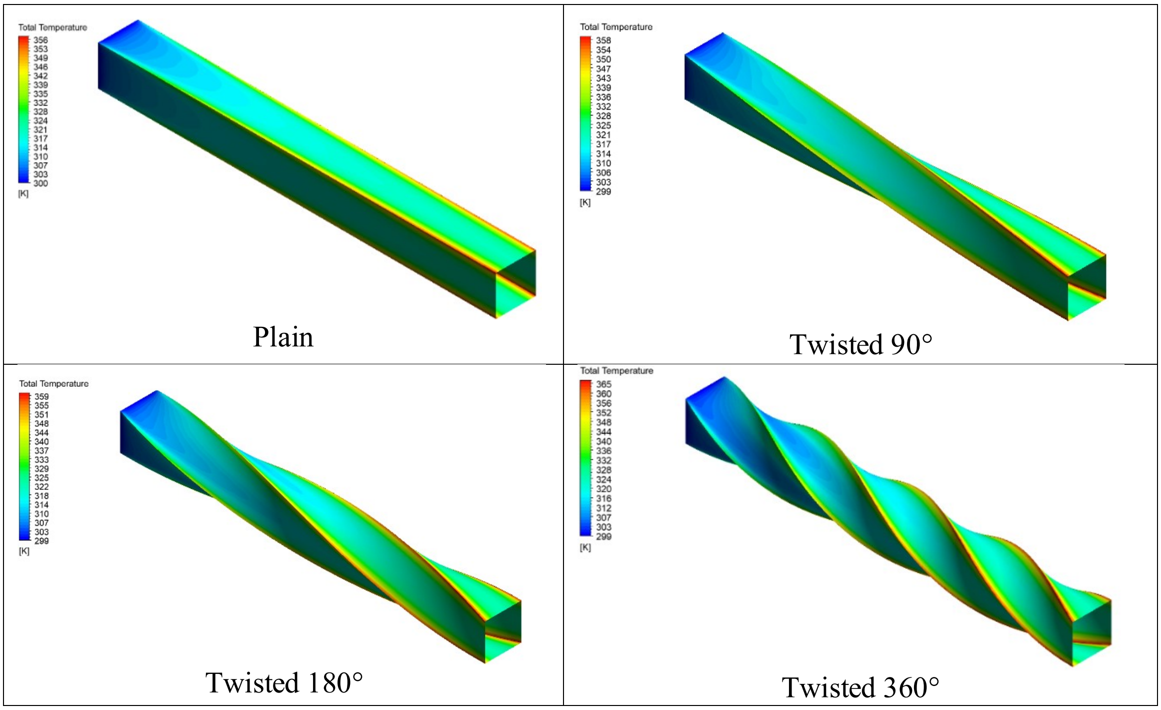

Fig. 4. Surface temperture for different configurations

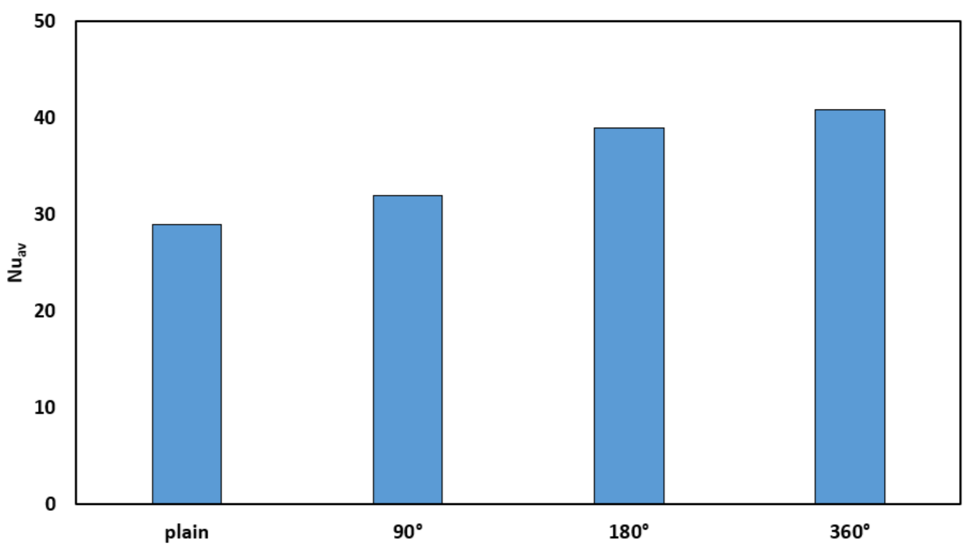

Fig. 5.Nusselt number for different configurations

4. CONCLUSIONS

In the present work the thermal performance of a heated air duct is investigated for different configurations for the test section including : plain, and twisted at angles of 90°,180° ,360°. The main conclusions can be summarized as :

- Twisting the air ducts increase the heat transfer due to the creation of secondary flows which disturb the thermal boundary layer. A small twist of 90° already provides a significant effect compared to ducts without twist.
- Twisting angle of 180° and 360° results in greater improvement in Nusselt number and more uniform surface temperature distribution, thereby maximizing heat transfer performance.
- Moreover, a higher twisting angle leads to a higher pressure drops, which is a significant design compromise to be assessed against the corresponding heat transfer increase.

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Conflicts of Interest:

The authors declare that there are no conflicts of interest to disclose.

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