Evaluation of velocity distribution utilizing the helically coiled tape in a conical diffuser

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Abstract. Numerical analyses study is reported on the flow characteristics in a conical diffuser with a helical tape insert. In this study, a rectangular tape of 5 mm width and 2 mm thickness is used inside the inner wall of the diffuser to induce additional recirculation. The numerical results are achieved for different Reynolds numbers (58035, 116072, 174108 and 232144) based on the inlet hydraulic diameter. The simulations are carried out with constant inlet condition considering the flow turbulent and incompressible. Air is used as a working fluid and maintained at constant room temperature. From a similar inlet condition, the results indicated that the velocity distribution is well enhanced.

1. Introduction
A swirl flow is one of the most vital parts in industrial combustion devices. The fluid flow contains a noticeable tangential velocity component and it can provide notable fluid distribution. These kinds of flows have received more attention. They are attractive for many heat transfer and mixing applications. Therefore, many studies were focused on the swirl flows. It is widely used in industrial combustion devices such as gas turbine combustors, furnaces, burners to provide power generation. It has a dominant effect on the mixing and distribution process in gas turbine combustion chamber [1-4].

The development and application of swirl flow generators have become an important issue in recent years due to the importance of the flow mixing and distribution enhancement. It is an effective method used to enhance the flow distribution and mixing through diffusers and pipes without the need to add any external power because it provides the flow with recirculation and helical motion and increase the tangential component of the velocity.

In order to address the flow characteristics, many researchers were evaluated various means of swirl flow generators such as helical screw-tape [5, 8] and twisted tape [9, 10]. Since many applications used helical screw-tape for velocity distribution and heat transfer enhancement, the helical screw-tape has become one the creative source for flow mixing enhancement.

Moreover, turbulent flow enhancement technology offers opportunities for advancements of flow mixing. Turbulent flows in passages with the gradually varying cross-sectional area are present in several applications in different engineering branches, especially where the geometric limitations are required like turbo-machinery. It has long been the subject of interest from the scientific community. Diffusers are devices of divergent area play an important role in many fluid machines to convert kinetic energy into pressure energy. Flow through diffuser has numerous industrial applications, and needs to be understood in more details. Therefore, a considerable amount of investigations on conical diffusers was carried out experimentally and numerically [11-14].

Fouad A. Saleh [15] investigated the thermal and fluid flow physical behavior of tubes fitted with helical screw twisted tape using distilled water and TiO₂ nanofluid as working fluids. The simulations
were achieved under turbulent Reynolds number range from 5,000 to 20,000. The results compared with a plain tube. The tubes with helical screw twisted tape showed better heat transfer rate when compared with a plain tube. The obtained results showed that a maximum enhancement of 82.2% is achieved in the Nusselt number by using tube fitted with dual helical screw twisted tapes inserts and nanofluid than that observed with the plain tube and distilled water.

Numerical simulations have successfully used by many authors to describe swirling flow. Therefore, the aim of the present numerical study is mainly on velocity distribution analysis utilizing helical tape insert positioned into the inside wall of a conical diffuser. The effect of different Reynolds numbers (58035, 116072, 174108 and 232144) on velocity distribution is simulated and analyzed by means of CFD software. All of the simulations are achieved at similar inlet conditions.

2. Numerical arrangements

2.1. Diffuser and helical tape geometries
The present investigation is performed with a conical diffuser consists of a square helical tape inside diffuser wall. The aim was to study the influences of the helical tape insert on the flow field structure, velocity distribution, and pressure distribution through the diffuser using air as a working fluid.

A numerical method is utilized for this investigation and all the simulations are solved under a similar inlet condition. The schematic geometries of the conical diffuser with a rectangular helical tape are shown in figure 1. The conical diffuser has a length (L) 140 mm, an inlet diameter (Di) 48 mm, an outlet diameter (Do) 145 mm, a helical tape width (h) 5 mm and a helical tape height (h) 2 mm. The helical tape arranged helically through the inside diffuser wall.

![Figure 1. Model geometries](image1.png)

![Figure 2. Model mesh generation](image2.png)

2.2. Boundary conditions arrangements
The work is performed under some assumptions to model the velocity profile in the conical diffuser fitted with a helical tape. The flow is assumed steady, turbulent and incompressible. Different inlet Reynolds numbers (58035, 116072, 174108 and 232144) are studied based on the hydraulic diameter of the conical diffuser (Dh) which is the inlet diameter of the diffuser (Di). The physical properties of the working fluid (air) at the conical diffuser inlet are constant. It has been considered as the density (1.225 kg/m³) and the dynamic viscosity (1.7894e − 05 kg/m.s). The pressure at the diffuser outlet is set to Atmospheric.
3. Numerical arrangements

3.1. Numerical simulation method
In this work, the computational domain for the tested model is created by Auto CAD software and uploaded to a commercial software ANSYS FLUENT 16.1. It is chosen as the CFD tool for this study. The grids are generated using the structured grid generator, ANSYS ICEM software. It is structured tetrahedral mesh generator software designed to automatically generate meshes in complex 2D and 3D geometries. Figure 2 shows a schematic of the grid generation for the numerical model. To evaluate the grid sizes on the numerical results accuracy, three grid sizes are tested. The results show that 17504 elements already satisfy mesh independent.

3.2. Governing equations
The governing equations of incompressible flow in the annular diffuser including conservation equations of mass, momentum, and energy are given as below:

- Mass Conservation Equation
  \[
  \frac{\partial}{\partial x_i}(r \rho u_i) = 0
  \]  
  (1)

- Momentum Conservation Equation:
  \[
  \frac{\partial}{\partial x_i}(r \rho u_i u_j) = -r \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ r \left( \mu \frac{\partial u_i}{\partial x_j} - \rho u_i u_j \right) \right]
  \]  
  (2)

- Energy Conservation Equation:
  \[
  \frac{\partial (\rho \bar{T})}{\partial x_i} + \frac{\partial (\rho \bar{u}_i \bar{T})}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \lambda \frac{\partial \bar{T}}{\partial x_i} \right)
  \]  
  (3)

where \( u \) is the inlet velocity magnitude, \( r \) is the inlet radius, \( \rho \) air intensity, \( P \) inlet pressure, the quantity represents the turbulent Reynolds stresses, \( \lambda \) is the thermal conductivity, and \( c_p \) is the specific heat at constant pressure.

3.3. Numerical model description
The calculations of turbulence kinetic energy \( k \) and its rate of dissipation \( \varepsilon \) are obtained from the following transport equations [16],

\[
K = 3/2 (u l)^2
\]  
(4)

\[
I = 0.16 (Re)^{-1/8}
\]  
(5)

\[
\varepsilon = (C_{\mu}^{3/4} K^{3/2}) l^{-1}
\]  
(6)

\[
l = 0.07 L
\]  
(7)

where \( u \) is the inlet velocity magnitude, \( I \) is the initial turbulence intensity, \( Re \) Reynolds number, \( C_{\mu} \) is a \( k-\varepsilon \) model parameter whose value is typically given as 0.09, \( l \) is the turbulence length scale and \( L \) is a characteristic length. For this study, \( L \) is considered as the hydraulic diameter.

4. Results and discussion
The Reynolds number \( Re \) is generally used to evaluate the velocity profile. Therefore, velocity distribution profile in a conical diffuser with a square helical tape insert is simulated for different Reynolds numbers (58035, 116072, 174108 and 232144) where the reference values are set at the inlet region.
4.1. Velocity profile
In order to display the air distribution induced by a rectangular helical tape insert, three cutting planes along the radial direction (zx direction) of the conical diffuser are studied. The planes are at 10 mm, 70 mm and 130 mm from the inlet. They are named (plane 1-1), (plane 2-2), and (plane 3-3), respectively as shown in figure 3. The variation of the predicted velocity profile at different air Reynolds number (58035, 116072, 174108 and 232144) are clarified in figures (3-10). From the figures (3-6) contours, they present the velocity distribution of airflow through a conical diffuser for the tested Reynolds numbers. The simulation results are utilized at three different planes in the radial direction.

![Figure 3. Velocity distribution contours in a conical diffuser for Re = 58035](image)

![Figure 4. Velocity distribution contours in a conical diffuser for Re = 116072](image)

![Figure 5. Velocity distribution contours in a conical diffuser for Re = 174108](image)

![Figure 6. Velocity distribution contours in a conical diffuser for Re = 232144](image)

The velocity variation has been seen clearly from these figures. As shown in these figures, the helical tape provides high-velocity distribution and this due to the increase of the turbulence and the tangential velocity component that will be induced by helical tape insert. The results verified that the distribution of the velocity through the diffuser in the flow direction decreases with increment in Reynolds number. In order to provide a more realistic visualization regarding the velocity distribution due to the helical tape insert, velocity vectors for different Reynolds number are presented in figures (7-10). For these figures, the direction of the vectors show clearly the distribution of the velocity and it increases as Reynolds number decrease. As can be seen, compared to these figures, there is an increase in the velocity vectors at the beginning of the diffuser and continuing through the divergent part. For Reynolds number (58035), the intensity of the air recirculation is very high that means the helical tape insert is effective. Downstream, the recirculation intensity is lower than in the inlet the diffuser due to a reduction of the separated region extent. Moreover, the simulation results show that Reynolds number (58035) has the highest recirculation intensity, followed by Reynolds numbers (116072,
174108 and 232144), respectively, which means the effect of helical tape insert gets weak. This latter effect is clearly more pronounced for the diffuser due to separation, which is the case characterized by the divergent area of the diffusers.

**Figure 7.** Velocity vectors in a conical diffuser for \( \text{Re} = 58035 \)

**Figure 8.** Velocity vectors in a conical diffuser for \( \text{Re} = 116072 \)

**Figure 9.** Velocity vectors in a conical diffuser for \( \text{Re} = 174108 \)

**Figure 10.** Velocity vectors in a conical diffuser for \( \text{Re} = 232144 \)

**Figure 11.** Velocity vectors in a plain conical diffuser
4.2. Velocity distribution comparison with helical tape insert

To study in more details the distribution of velocity due to the helical tape insert, a comparison of velocity distribution for different Reynolds numbers are performed. Figures (12-14) show the velocity distribution at three planes named; plane 1-1, plane 2-2 and plane 3-3 for various Reynolds numbers (58035, 116072, 174108 and 232144).

In figure 12, the velocity distribution for plane 1-1 at the tested Reynolds numbers is shown. It presents the variation of velocity in a radial direction of the diffuser. The curves here illustrate the classically simple situation of fluid flow entering a diffuser with a conical inlet of diameter D and length L with a uniform velocity profile. Figure 13 represents the velocity distribution for plane 2-2. In this part of the flow, it remarked that turbulence and recirculation start to affect the flow behavior. It is clear that recirculation and separation increase as Reynolds number increases. The variation of velocity distribution at plane 3-3 is shown in figure 14 for the tested Reynolds numbers. As shown in this figure, the velocity distribution increases for all values of Reynolds number with the helical tape insert. It is worth mentioning that the airflow disturbance in the diffuser changes from the airflow disturbance in the center to the flow disturbance near the wall. When the flow disturbs the air near the wall, the velocity gradient enhances near the diffuser wall. Moreover, recirculation creates by the insert of the helical tape inside the diffuser wall enhance the velocity distribution.

![Figure 12. Velocity distribution at plane 1-1](image1)

![Figure 13. Velocity distribution at plane 2-2](image2)

![Figure 14. Velocity distribution at plane 3-3](image3)
5. Conclusion
In this paper, numerical simulations were presented and analyzed to enhance the velocity distribution in a conical diffuser. The work was performed by inserting a rectangular helical tape and assuming air as a working fluid. Four different Reynolds numbers (58035, 116072, 174108 and 232144) are investigated to get information about the improvement ability of the helical tape as a distributor. In order to study the air distribution in details, three cutting planes (plane 1-1, plane 2-2 and plane 3-3) in the radial flow direction are simulated.

The rectangular helical tape insert increases the recirculation and the helical motion by increasing the tangential velocity components. It has a good advantage compared with the plain conical diffuser (without helical tape). From the above analyses, we can increase and enhance the distribution characteristics. The main purpose of the study is to compare the results obtained in the conical diffuser, also analyzed the recirculation, where the objective of enhancing the velocity distribution results is reached.

6. Appendices

![Figure 15. Velocity profile in a plain conical diffuser](image1)

![Figure 16. Velocity profile in a conical diffuser with helical tape insert at v = 20 m/s](image2)
Figure 17. Velocity profile in a conical diffuser with helical tape insert at \( v = 40 \text{ m/s} \)

Figure 18. Velocity profile in a conical diffuser with helical tape insert at \( v = 60 \text{ m/s} \)

Figure 19. Velocity profile in a conical diffuser with helical tape insert at \( v = 80 \text{ m/s} \)

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