World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:10, No:3, 2016

Temperature Distribution Enhancement in a Conical Diffuser Fitted with Helical Screw-Tape with and without Center-Rod

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Open Science Index, Mechanical and Mechatronics Engineering Vol:10, No:3, 2016 publications.waset.org/10003907.pdf

***Abstract*—**Temperature distribution investigation in a conical diffuser fitted with helical screw-tape with and without center-rod is studied numerically. A helical screw-tape is inserted in the diffuser to create swirl flow that helps to enhance the temperature distribution rate with inlet Reynolds number 4.3 x 10^4. Three pitch lengths ratios (Y/L = 0.153, 0.23 and 0.307) for the helical screw-tape with and without center-rod are simulated and compared. The geometry of the conical diffuser and the inlet condition for both arrangements are kept constant. Numerical findings show that the helical screw-tape inserts without center-rod perform significantly better than the helical tape inserts with center-rod in the conical diffuser.

***Keywords*—**Diffuser, temperature distribution, CFD, pitch length ratio.

I. Introduction

A diffuser is a device of a divergent area, while the cross-section area of diffuser increases in the direction of flow, the fluid is decelerated as it flows through it causing a rise in static pressure along the stream. This process is known as diffusion. With this important characteristic the diffusers present several applications in different engineering branches, especially where the geometric limitations are required. In such applications, diffusers needed to be specially designed so as to achieve maximum pressure recovery and avoiding flow separation. It is widely used in gas turbines, pumps, fans, wind tunnels, etc.

Heat transfer and flow dynamics in pipes and diffusers have enjoyed strong attention of both numerical and experimental research on over the past years. The enhancement of heat transfer is the process of improving the performance of a heat transfer system by increasing the heat transfer coefficient. Through the past decades, heat transfer enhancement technology has been developed and widely used in many applications; for example, aerospace applications, gas turbines, combustion chambers and heat exchangers. These techniques can be categorized to active and passive techniques. The active technique required external power such as surface vibration, fluid vibration, electric, suction and injection, while the passive techniques don't need an external power for example, rough surface, extended surface, surface tension devices, and swirl flow devices. The passive techniques are beneficial compared with active techniques; because the manufacturing process for these techniques are simple and can be easily employed to the existing application. It has been pointed out that the passive techniques can play an important role in the heat transfer enhancement if a proper configuration of the inserts being selected depends on working conditions [1], [2].

Swirling flow as mentioned earlier is one of the passive techniques. It is usually accompanied with high tangential velocity and turbulence intensity, which provides an additional mechanism to increase the heat transfer rate [3]-[8].

The principle of heat transfer enhancement in the core flow of tube with helical screw-tape inserts was studied [9]. The aim was to improve the temperature uniformity and to reduce the flow resistance. The simulation results showed that the average overall heat transfer coefficients in circular plain tubes were enhanced with helical screw-tape of different widths by as much as 212- 351%.

S. Eiamsa-ard et al. [10] described heat transfer enhancement caused by helically twisted tapes. Each helically twisted tape was fabricated by twisting a straight tape to form a typical twisted tape then bending the twisted tape into a helical shape. The experiments were performed with three different twist ratios y/W of (2, 2.5, 3) and three different helical pitch ratios p/D of (1, 1.5, 2) at Reynolds number ranged between 6000 -20000. For all cases, heat transfer rate tended to increase with increasing Reynolds number, as a result of increased turbulence intensity. Moreover, findings showed that at similar conditions, heat transfer rate and friction factor increased as the tape twist ratio and helical pitch ratio decreased. Gül et al. [11] found that an increase of heat transfer rate up to 20% could be achieved by the insertion of a short helical tape placed at the entrance of a circular tube.

Numbers of numerical and experimental studies have been made to report the effect of utilizing helical screw-tapes with and without core-rod. S. Eiamsa-ard et al. [12] confirmed that Nusselt number increased by 160% for the full-length helical screw-tape with core-rod, and 150% for the full-length helical screw-tape without core-rod in comparison with the plain tube. The increase in heat transfer and pressure drop can be explained by the swirling flow as a result of the secondary flows of the fluid. It was observed that there were strong swirling flows in the tube fitted with the helical screw-tape with a core-rod, while the weak swirling flow was seen in the helical screw-tape without a core-rod.

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Deshmukh et al. [13] performed a numerical study of heat transfer augmentation for circular tube fitted with full length helical screw-tape with and without core-rod. Numerical findings pointed out that the tape with core-rod caused higher heat transfer rate than that without core-rod. The results have been explained as follow, this could be due to a flow mixing behavior between two streams for using the tape without core-rod, and these two streams included the swirling flow around the tape combined with the axial flow along the tape core. Therefore, this mixing between these two streams made swirling flow weaker than that from using the tape with core-rod which has a swirling flow only.

This work numerically presents the effect of helical screw-tape with and without center-rod on the temperature profile at the outlet.

II. NUMERICAL MODELING

A. Diffuser with Helical Screw-Tape Geometry with /without Center-Rod

The diffuser and the helical screw-tape with and without center-rod geometries represent in Figs. 1 and 2, respectively.

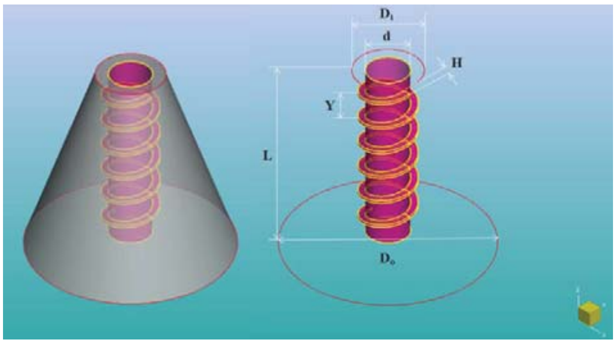

Fig. 1 Helical screw-tape inserts geometries with center-rod

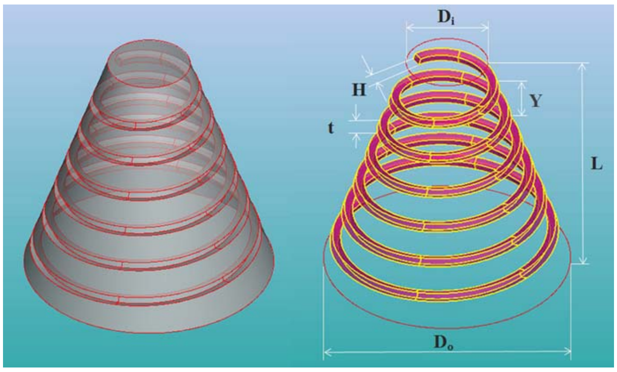

Fig. 2 Helical screw-tape inserts geometries without center-rod

The tested diffuser has 48 mm inlet diameter (D_i), 145 mm outlet diameter (D_o) and 140 mm length (L). The helical screw-tape inserts have the geometric dimensions of height length (*H* = 5 mm) with center-rod diameter (d = 30 mm) and thickness of (t = 2 mm) as shown in Figs. 1 and 2. The test was conducted with three different pitch lengths (*Y* = 20 mm, 30 mm and 40 mm). The helical screw-tape geometries were the same for both tested arrangements. Three different pitch length ratios (*Y/L* = 0.153, 0.23 and 0.307) were simulated for both diffusers. Typical values of boundary conditions are given in Table I.

TABLE I
BOUNDARY CONDITIONS

Parameters/Properties	**Value**
Inlet pressure, P_i	2.89 [bar]
Inlet Temperature, T_i	870.266 [K]
Dynamic Viscosity, μ	3.935×10^{-5} [kg/m.s]
Air density, ρ	1.156 [kg/m^3]
Reynolds Number, Re	4.3×10^4
Inlet velocity of air, V_i	80.6 [m/s]
Mass flow rate of air, $\dot{m}$	0.1027 [kg/s]

B. Computational Model

In the present work numerical study was conducted with a helical screw-tape inserts in a conical diffuser with and without center-rod. The commercial software NUMECA FINE^{TM} /Open *v*3.1 was chosen as the CFD tool for this study. The standard *k*-ε model was applied as a turbulence model and the numerical analyses were performed in three dimensional domains. The turbulence kinetic energy *k* and its rate of dissipation ε calculations followed literature reference. Standard *k*–ε turbulence model was allowed to predict the heat transfer and fluid flow characteristics. This turbulence model has been successfully applied to flows with engineering applications including internal flows [14]. The turbulence kinetic energy *k*, and its rate of dissipation ε, was obtained from the following transport equations [15]:

$$k = \frac{3}{2}\left(V\,I\right)^2 \tag{1}$$

$$I = 0.16\left(Re\right)^{-\frac{1}{8}} \tag{2}$$

$$\varepsilon = \left(C_\mu^{\frac{3}{4}} . k^{\frac{3}{2}}\right).\; l^{-1} \tag{3}$$

$$l = 0.07\,L \tag{4}$$

where, *V* is the inlet velocity magnitude, *I* is the initial turbulence intensity, Re Reynolds number, C_μ is a *k*-ε 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.

Fig. 3 (a) displays mesh generation of the helical screw-tape inserts in a conical diffuser with a center-rod for 1836273 cells. Fig. 3 (b) depicts mesh generation of the helical screw-tape inserts in a conical diffuser without a center-rod for 1247022 cells.

C. Grid Independence Study

The grid independence studies have been performed to evaluate the effects of grid sizes on the accuracy of the numerical solutions results. For this study, the grid independent test was conducted by using different number of grid cells and calculates the outlet static temperature.

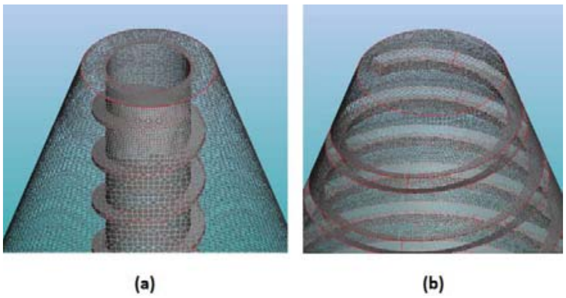

Fig. 3 Mesh generation for the helical screw-tape inserts in a conical diffuser fitted with and without center-rod

Five different meshes with total number of cells 852677, 1325728, 1624027, 2010342 and 3028988 were initially considered for grid independence study for the conical diffuser fitted with helical screw-tape without center-rod. This independence study was performed to verify the numerical results as presented in Fig. 4. The results of the static temperature at the outlet plane were compared for all the simulations. The grid system 1624027 with difference percentage 0.35% was adequately dense for the simulations. Moreover, another grid independence test has been completed for the conical diffuser fitted with helical screw-tape with center-rod by using five different grid systems, 909611, 1478903, 1987719, 2665107 and 3567624 grids (cell number). A domain with mesh volumes of 1987719 recorded a small percentage of difference up to 0.65%, so it was chosen to complete these simulations as shown in Fig. 5.

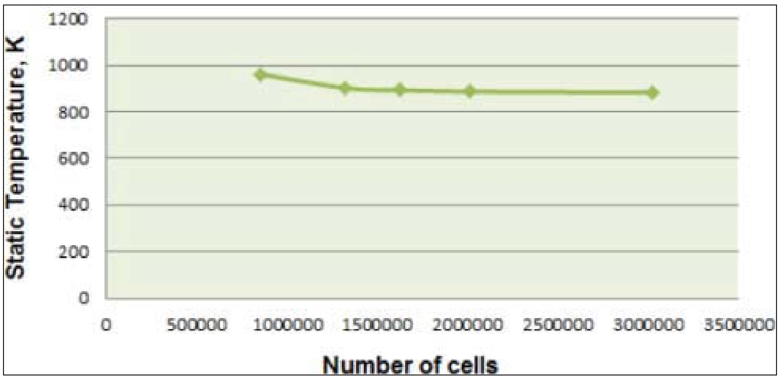

Fig. 4 Grid independence test for a conical diffuser fitted with a helical screw-tape inserts with center-rod

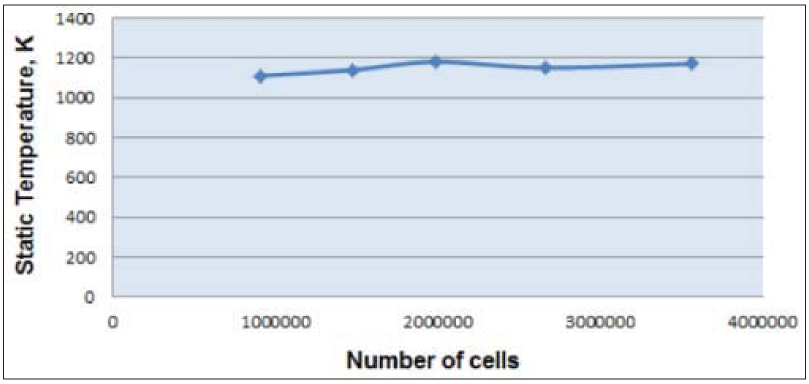

Fig. 5 Grid independence test for a conical diffuser fitted with a helical screw-tape inserts without center-rod

D.Heating Arrangement

To analyse the temperature distribution, a spherical heat source of 10 kW with a radius of 0.005 m was put in the diffuser at 22 mm from the longitudinal axis, 23 mm downstream of the inlet section as shown in Fig. 6. The heat source was fitted with the beginning of the tested swirl generator models that include helical screw-tape with and without center-rod. The unsymmetrical location was purposely chosen in order to better observe the swirling motion.

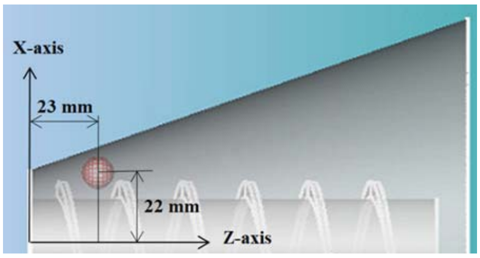

Fig. 6 Heat source position

E. *Cutting Planes*

This study was focused on swirling flow induced by the insertion of a helical screw-tape in a conical diffuser. Three different planes in the radial direction were applied for the tested diffuser to analyse the influence of the aforementioned swirl generator models on the temperature distribution. The planes were chosen at 30 mm (plane 1-1), 70 mm (plane 2-2) and 111 mm (plane 3-3) from the tested diffusers inlet.

Figs. 7 (a) and (b) present the proposed planes in the tested diffuser.

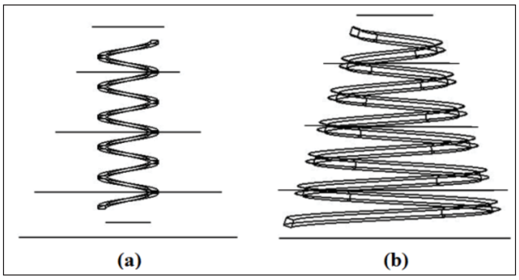

Fig. 7 Three planes in the radial direction of the tested diffuser

III. MATHEMATICAL MODELS

Fluid flows including gas and liquid are governed by partial differential equations which represent conservation laws for the mass, momentum and energy. The continuity and the momentum equations are the mathematical equations that used to describe the flow of fluids. These equations describe the conservation of mass, momentum, and energy which also known as the Navier-Stokes equations. In principle, the Navier-Stokes equations describe both laminar and turbulent flows. In Cartesian tensor nations, the Navier-Stokes governing equations for steady compressible flows will take the form as follows, [16]-[18].

$$\frac{\partial}{\partial x_i}\left(r\rho u_i\right)=0 \tag{5}$$

$$\frac{\partial}{\partial x}\left(r\rho u_i u_j\right)=-r\frac{\partial \mathrm{P}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[r\left(\mu\frac{\partial u_i}{\partial x_j}-\rho\overline{u_i^{'}u_j^{'}}\right)\right] \tag{6}$$

where, the quantities $-\overline{\rho u_i u_j}$ represent the turbulent Reynolds stresses produced by velocity fluctuations $u_i^{'}$.

$$\frac{\partial\left(\rho\overline{T}\right)}{\partial x_i}+\frac{\partial\left(\rho\overline{u_i}\,\overline{T}\right)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\lambda}{C_p}\frac{\partial\left(\overline{T}\right)}{\partial x_i}\right) \tag{7}$$

where, λ is the thermal conductivity, and C_p is the specific heat at constant pressure.

IV. RESULTS AND DISCUSSIONS

Figs. 8-10 present temperature distribution of the helical screw-tape insert with different pitch length ratios in a conical diffuser with and without center-rod. In the figures, three different pitch length ratios, include (*Y/L* = 0.153, 0.23 and 0.307) are displayed. Each pitch length represents three cutting plane. It is observed that the temperature will be forced to distribute in the radial direction due to the existence of the helix in both tested arrangements. Apparently, from the aforementioned figures, it can be seen that the existence of the helical screw-tape hub leads the temperature to distribute through the three cutting planes. With the presence of the helix, the distribution is mainly caused by the increase of turbulent intensity due to the existence of the helix. In the obtained results, temperature distribution increases with decreasing the pitch length ratio (*Y/L*) as shown in the mentioned figures. A reason is that as pitch length ratio (*Y/L*) decreases, flow area in the conical diffuser decreases resulting in an increasing of turbulent intensity between each pair of the helix.

A. *Effect of Helical Screw-Tape Inserts in Diffuser with and without Center-Rod for Pitch Length Ratio (Y/L = 0.153)*

Fig. 8 reveals the effect of helical screw-tape inserts in diffuser with and without center-rod for pitch length ratio (*Y/L* = 0.153). For these three radial planes, it can be seen that the helical screw-tape inserts without center-rod can help to promote higher temperature distribution than the use of helical screw-tape inserts with center-rod.

B. *Effect of Helical Screw-Tape Inserts in Diffuser with and without Center-Rod for Pitch Length Ratio (Y/L = 0.23)*

Fig. 9 represents the influence of helical screw-tape inserts in diffuser with and without center-rod for pitch length ratio (*Y/L* = 0.23). The temperature distribution variation through the three planes is in the same sequence with the distribution shown in Fig. 8; however, the area of distribution that displayed in Fig. 9 is smaller than that at Fig. 8.

C. *Effect of Helical Screw-Tape Inserts in Diffuser with and without Center-Rod for Pitch Length Ratio (Y/L = 0.307)*

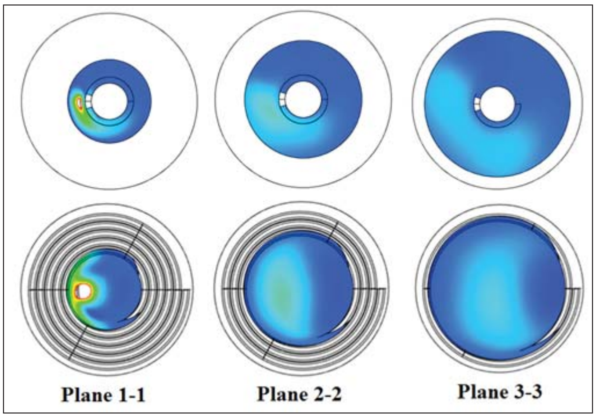

Fig. 8 Three radial planes represent temperature distribution in a conical diffuser fitted with a helical screw-tape with and without center-rod for pitch length ratio (*Y/L* = 0.153)

Fig. 10 shows the impact of helical screw-tape inserts in diffuser with and without center-rod for pitch length ratio (*Y/L*

= 0. 307). From the figure, it is clear that the distribution phenomena seem to be similar to Figs. 9 and 8.

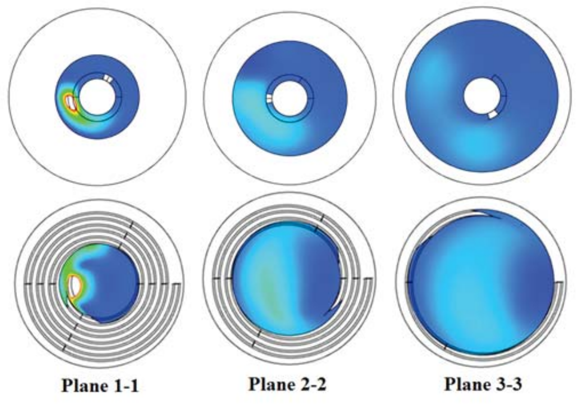

Fig. 9 Three radial planes represent temperature distribution in a conical diffuser fitted with a helical screw-tape with and without center-rod for pitch length ratio (*Y/L* = 0.23)

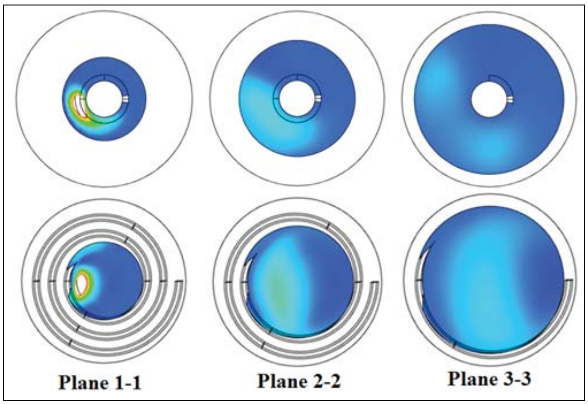

Fig. 10 Three radial planes represent temperature distribution in a conical diffuser fitted with a helical screw-tape with and without center-rod for pitch length ratio (*Y/L* = 0.307)

Figs. 11-13 display the variation of temperature distribution at the outlet plane. In the figures, the influence of the helical screw-tape inserts with and without center-rod is shown. As expected from all figures, the temperature distribution obtained from the conical diffuser fitted with helical screw-tape inserts without center-rod was significantly higher than that of helical screw-tape inserts with center-rod.

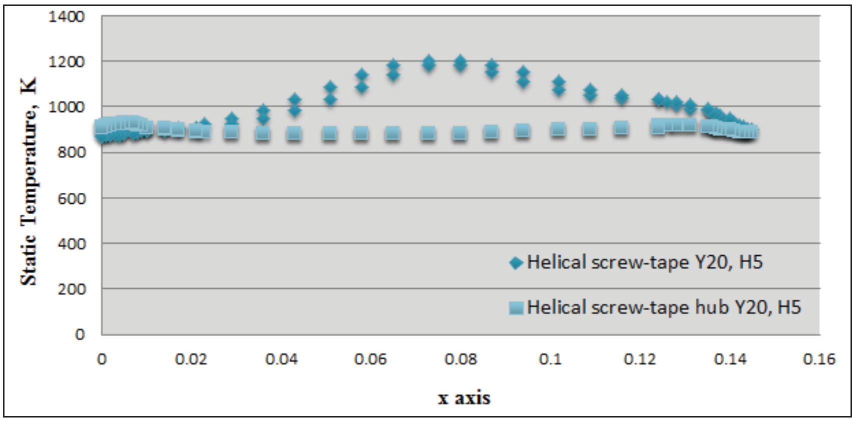

Fig. 11 Variation of outlet plane temperature distribution in a conical diffuser fitted with a helical screw-tape with and without center-rod for pitch length ratio (*Y/L* = 0.153)

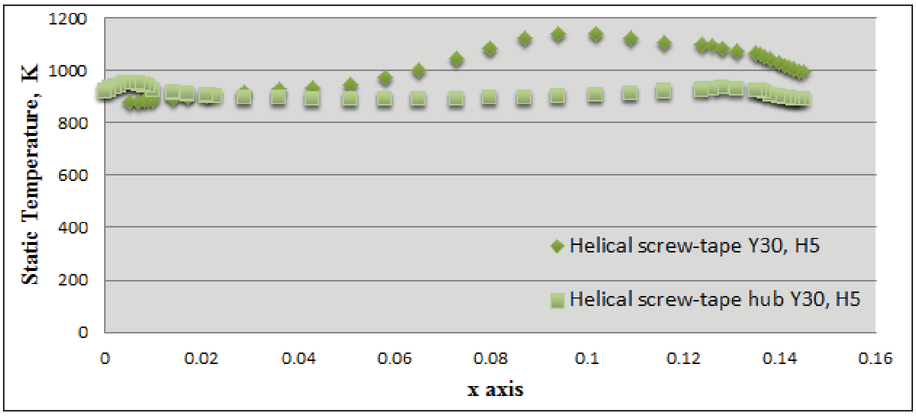

Fig. 12 Variation of outlet plane temperature distribution in a conical diffuser fitted with a helical screw-tape with and without center-rod for pitch length ratio (*Y/L* = 0.23)

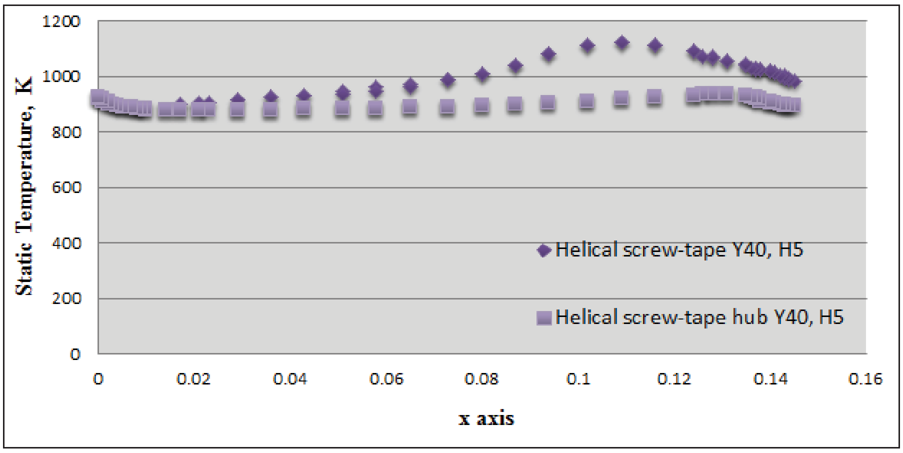

Fig. 13 Variation of outlet plane temperature distribution in a conical diffuser fitted with a helical screw-tape with and without center-rod for pitch length ratio (*Y/L* = 0.307)

V. CONCLUSION

Numerical work has been conducted to investigate the temperature distribution in a conical diffuser containing a helical screw-tape with and without center-rod. Based on the numerical simulation results, the following conclusions can be made:

1) The helical screw-tape insert has a significant effect on enhancing temperature distribution.
2) In comparison between the helical screw-tape with and without a center-rod, it can be seen that the helical screw-tape without rod yields higher temperature distribution than that with center-rod.

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