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RESEARCH NOTE

Investigation of Thermo-hydraulic Performance of Circular Tube Fitted with Center-cleared Twisted Tape Using CFD Modeling

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ABSTRACT

The article presents a practical technique for enhancing thermo-hydraulic performance of a circular tube. In this way, numerical method focusing on laminar tubular flow is used to compare the effectiveness of utilizing center-cleared twisted tapes instead of typical shape of short width tapes. Numerical analysis represented that using both center-cleared and typical shape of twisted tapes, Re enhancement reduces the flow resistance. Studying short width twisted tapes showed that decreasing the width of twisted tape, reduces the heat transfer and hydraulic performance. Contrarily, using sufficient clearance for center-cleared twisted tapes can increase the heat transfer. Hence, applying center-cleared twisted tape as a tool of enhancing heat transfer can be a promising and practical idea.

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NOMENCLATURE

W	Width of the twisted tape, m	C_p	Specific heat at constant pressure, $Jkg^{-1} K^{-1}$
H	180 degree twisted pitch of the tape, m	q	Heat flux density, Wm^{-2}
C	Width of the central clearance, m	h	Heat transfer coefficient, $Wm^{-2}K^{-1}$
L	Length of the tube, m	u	Flow velocity, ms^{-1}
D	Inner diameter of the tube, m	u_c	Flow velocity at the centerline of the tube, ms^{-1}
R	Inner radius of the tube, m	Δp	Pressure drop between tube entry and exit, Nm^{-2}
r	Radial distance, m	Nu	Nusselt number
x_i	Space coordinates in Cartesian system, m	f	Friction factor
w	Tape width ratio, W/D	Re	Reynolds number
c	Central clearance ratio, C/D	Pr	Prandtl number
k	Thermal conductivity of fluid, $Wm^{-1}K^{-1}$	δ	Thickness of the twisted tape, mm
T	Temperature, K	ρ	Fluid density, kgm^{-3}
T_c	Temperature at the centerline of the tube, K	μ	Fluid dynamic viscosity, $kgm^{-1}s^{-1}$

1. INTRODUCTION

Heat exchangers are widely used in various areas such as power production, chemical and food industries, environmental engineering, waste heat recovery, the manufacturing industry, air conditioning, refrigeration and space applications. Heat enhancement technology plays an important role in conserving energy and protecting the environment. Single-phase heat transfer can be increased using artificially roughened surfaces and other augmentation techniques such as vortex generators and modifications to duct cross-sections and surfaces. These augmentation techniques belong to the passive category, which can increase the convective heat transfer coefficient on the tube side. Among the many techniques investigated for the augmentation of heat transfer rates inside of round tubes, a wide range of inserts, such as tapered spiral inserts, pickings, rings, disks, streamlined shapes, mesh inserts, conical-nozzles,

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and V-nozzles [1], have been used to minimize the size of heat exchangers and thus reduce the capital investments for a given load. The insertion of twisted tape into a tube is an attractive method to improve the convective heat transfer coefficient in existing systems because it generates a swirl flow, which can induce a tangential flow velocity component and enhance fluid mixing between the duct core and the near-wall region. Klaczak [2] investigated the pressure drop and heat transfer variation using swirl generators like twisted tapes. Eiamsa-ard et al. [3] verified parameters such as thermal performance factor, friction factor and heat transfer in their test section equipped with short-length twisted tapes. They claimed that using full-length tapes makes higher thermal performance in comparison with short length twisted tapes. Some researchers also tried on the impact of nanofluids on heat transfer and friction factor in circular tubes with twisted tapes inserts like [4-8]. Bharadwaj et al. [9] studied heat transfer behavior for both laminar and turbulent flow in tube fitted with twisted tape swirl generators. Their results confirm that twist direction noticeably affected thermo-hydraulic characteristics. Thianpong et al. [10] focused on pressure drop and heat transfer enhancement using twisted tape swirl generators in dimpled tubes with different pitch ratios. Akhavan-Behabadi et al. [11] also made effort on heat transfer and pressure drop during flow boiling of R-134a, inside a horizontal evaporator with twisted tape. They found sensitive pressure drop penalty while enhancing heat transfer by this technique. Kazuhisa et al. [12] studied heat transfer mechanism and local Nusselt number affected by mixing flow and secondary flow caused by twisted tapes. Chang et al. [13] and Saha et al. [14], analyzed the effect of Reynolds number and twist width on thermal behavior of flow in tubes.

Normally, the short-length twisted tape can increase the heat transfer coefficient in the tube by generating a swirl flow, although the swirl flow gradually decays downstream between the short-length twisted tapes. The most attractive advantage is that the flow resistance in the free space (the section without short-length twisted tape) is lower than that with full-length twisted tape. This effective heat transfer enhancement technology has attracted the interest of researchers.

Although many researchers studied widely on heat transfer enhancement in tubes and ducts [12, 15-18], verification of twisted tape effect on heat transfer increment accompanied with a low friction factor is still noteworthy. Accordingly, in this work center-cleared twisted tape is assumed to be a good option for heat transfer enhancement. This type of twisted tapes disturbs the boundary layers and mixes them, while upwind area blocking the flow is reduced. Thus, it is expected to have a relatively sensible connective heat transfer enhancement and low flow resistance. Since the idea can be easily implemented in heat exchangers tube, it can be deeply investigated through the available tools. Here, the heat transfer and friction factor characteristics of laminar flow in a circular tube fitted with the center-cleared twisted tape will be investigated through numerical simulation and the results will clarify the idea.

2. PHYSICAL MODEL

The geometries of the conventional, short-width and center-cleared twisted tapes are depicted in Figure 1. Twisted tapes with thickness (δ) of 0.001 m are fitted in the full length of all tubes. The diameter (D) and length (L) of the tube are 0.02 m and 0.5 m, respectively. The 180 deg twist pitch (H) is 0.05 m and thus the relative twisted ratio (H/D) is 2.5. The effects of the tape width ratio (w=W/D) and central clearance ratio (c= C/D) on the heat transfer and friction factor characteristics will be investigated. Parameters like the Reynolds number (Re), Nusselt number (Nu), friction factor (f) and thermal performance factor (h) are defined as follows:

$$\mathrm{Re} = \frac{\rho u D}{\mu} \tag{1}$$

$$Nu = \frac{hD}{k} \tag{2}$$

$$f = \frac{\Delta p}{\left(\rho u^2/2\right)\left(L/D\right)} \tag{3}$$

Water which is assumed to be incompressible fluid is selected as the working fluid in this issue. The natural convection has been neglected and the thermo-physical properties of fluid are assumed to be temperature independent.

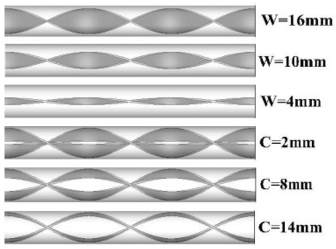

Figure 1. Different geometries studied in this effort

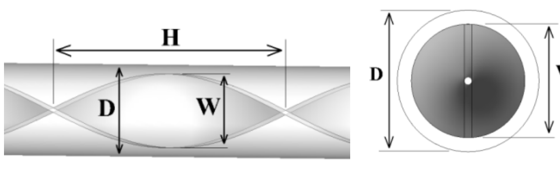

Figure 2. Short width twisted tape

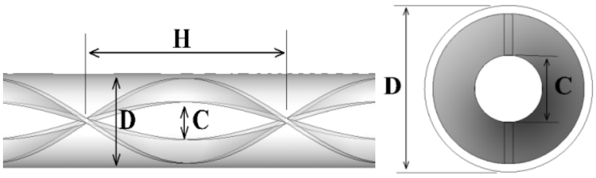

Figure 3. Center-cleared twisted tape

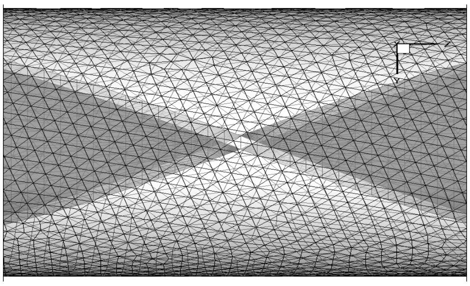

Figure 4. Tetrahedral meshing

The Reynolds numbers referred to the inlet values are set at 500, 750, 1000, 1250, 1500 and 1750 in the computations.

3. MATHEMATICAL MODEL

The problem under investigation is considered to be three dimensional, laminar and steady. Heat conduction in the twisted tape is neglected. Equations of continuity, momentum and energy for the fluid flow are given below:

Continuity equation

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

Momentum equation

$$\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right] \tag{5}$$

Energy equation

$$\frac{\partial}{\partial x_j}\left(\rho u_i C_p T-k\frac{\partial T}{\partial x_j}\right)=0 \tag{6}$$

At the inlet, the fully developed profiles of velocity and temperature are specified, as shown in (7) and (8), respectively. At the outlet, a pressure-outlet condition is used. A constant heat flux is imposed on the tube wall. On the surfaces of the tube wall and twisted tape, no slip conditions are applied.

$$u=u_c\left(1-\frac{r^2}{R^2}\right) \tag{7}$$

$$T=T_c+\frac{qR}{k}\left[\left(\frac{r}{R}\right)^2-\frac{1}{4}\left(\frac{r}{R}\right)^4\right] \tag{8}$$

where, uc and Tc are the velocity and temperature at the centerline of the tube, respectively. q is the heat flux density on the tube wall. R is the inner radius ofthetube, and r is the radial distance.

4. NUMERICAL METHOD

Computation fluid dynamic commercial software Fluent 6.3.26 is chosen as a tool for this investigation. Fluent applies finite volume method to solve the governing equations with respect to the boundary conditions of the problem. The standard pressure and second order upwind discretization schemes for momentum and energy equations are employed in the numerical model. The pressure-velocity coupling is handled by the 'SIMPLE' algorithm. At the initial time, the under relaxation factors are also considered to be 0.3 and 0.7 for pressure and momentum, respectively. After some iteration the momentum under relaxation was gradually reduced to 0.3 to have more exact convergence. Also, for all simulations the convergence criteria was of 10^{-5} for continuity and velocity components and 10^{-6} for energy.

In order to have exact numerical simulation which covers the problem features, good quality mesh generation is necessary. Because of twisting geometry of the problem, tetrahedral elements are used for meshing the whole field (Figure 4).

In addition, fine meshes were needed for near wall regions, grid independency of the problem defined required mesh size to have acceptable results. For this purpose, three grid systems with about 690000, 880000 and 1220000 cells are adopted for a specific case with Reynolds number of 1000 and the tape width ratio of 0.8.

The Nusselt number and friction factor for the base case are shown in Figures 5 and 6. The variation trend in these two figures imply that grid system with 880000 cells can be a good grid system for this problem, since there is no more noticeable improvement in the results with respect to grid number and calculation time enhancement.

In order to evaluate the numerical tool efficiency, the plane tube was considered to be the comparison case for the numerical result and theoretical available data. In Figure 7, there is small deviation for the two scenarios. So, the utilized numerical tool and the grid system chosen for investigation can be liable for the study.

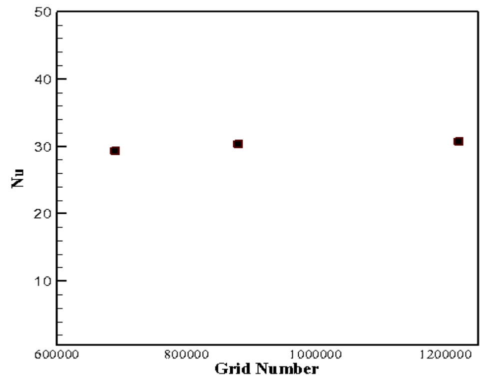

Figure 5. Nusselt number for different grid systems

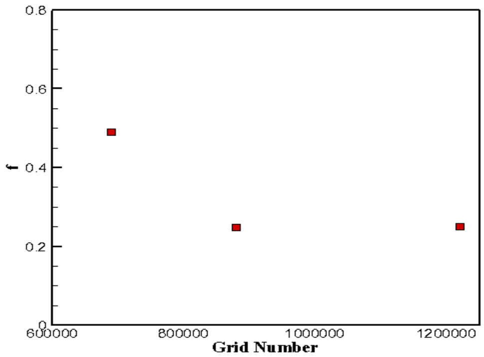

Figure 6. Friction factor for different grid systems

5. RESULT & DISCUSSION

In this article, the effect of twisted tape width on Nusselt number and friction factor was verified numerically for different Reynolds numbers in laminar flow. Figures 8 and 9 demonstrate that increasing the Reynolds number yields to enhancement of convectiveheat transfer (Nusselt number as an indicator), and reduction of friction factor. This is mainly because of intensification of twisted tape blending effect at the central region of the tube resulted from Re number enhancement. It is also seen that, as the width ratio of the twisted tape decreases, the heat transfer for each definite Re number diminishes. This is also due to the effect of twisted tape being weakened by width reduction. Contrarily, widening the twisted tapes, made greater Nusselt number. Moreover, it is noted that when w is relatively large, Nu decreases more quickly. If w is decreased more, the variation of Nu number slows down.

Two main reasons of why w reduction weakens the heat transfer are that: as the width of the tapes is reduced, (1) the mixing of the fluid is weakened due to disturbance reduction occurred in boundary layers. (2) the swirl flow generated by twisted tape is reduced. Also, it is seen that reducing the tape width decreased the friction factor. For each definite Re number thisissue was confirmed. Moreover, when w is somehow large, variation of friction factor is not so fast. Central clearance ratio was the idea for improving thermal behavior of the tube and it was tested in laminar flow criteria for different Reynolds number. As seen before, shortening the tape edge from its sides weakened heat transfer. Comparing the curves in this part, it can be concluded that not only using center cleared technique does not weaken heat transfer, but also to some extent improves the thermal characteristics of the flow.

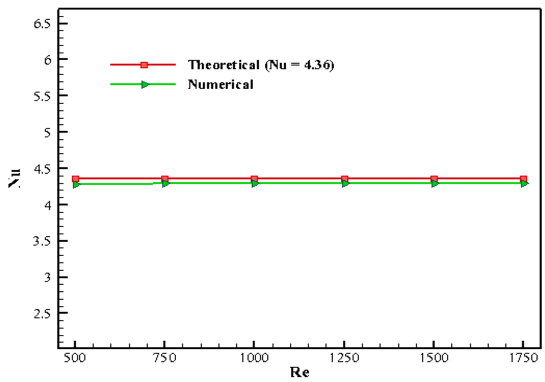

Figure7. comparison of the numerical results and theoretical data for the Nusselt number

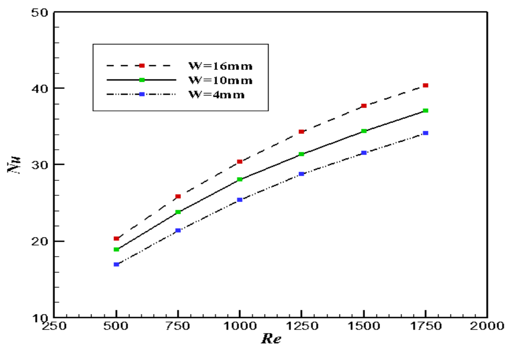

Figure 8. Nusselt number in different Reynolds number

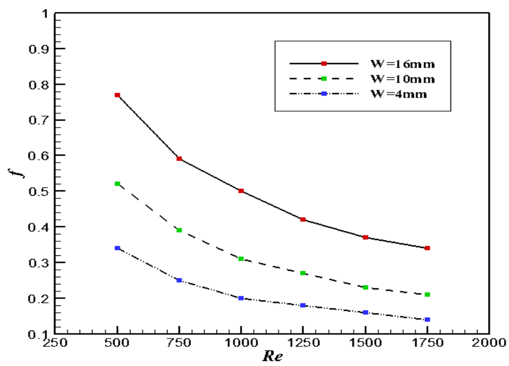

Figure 9. Friction factor in different Reynolds number

Figure 10 represents the results for Nusselt number. It is understood that, even a small clearance in the middle of the tape can improve thermal behavior of the tube in comparison with the simple twisted tape with w=0.8 in all range of Re numbers. Justification for this claim is that, as we know the swirl flow generated by twisted tape evokes the idea for heat transfer enhancement. Correspondingly, cutting the tape from middle surface makes the flow trend more complicated and this helps better mixing of the boundary layers. In other words it can be said that in center cleared cases the effect is duplicated. The second effect which is born by the clearance in the tape is usually useful for low Reynolds number where original swirling flows are very weak.

Figure 11 also represents the effect of center cleared twisted tapes on friction factor. As it is obvious, for greater clearance the blocking area is reduced and as a result friction factor decreased. Also, reduction of friction factor is more noticeable in low Reynolds number.

For more concentration on the effects of the twisted tapes on flow thermal behavior, the case of Re=1000 was chosen to be scrutinized. Subsequently, the middle section of the tube in L=0.25m was cut to see the flow behavior more precisely.

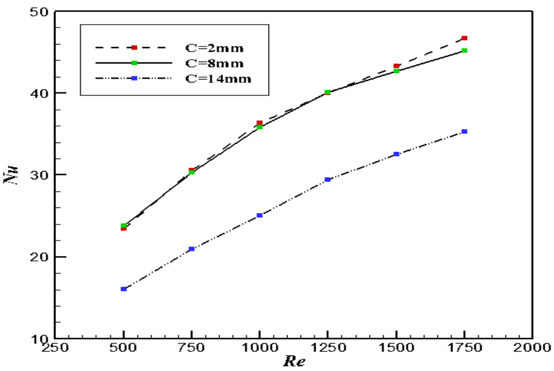

Figure 10. Nusselt number in different Reynolds number

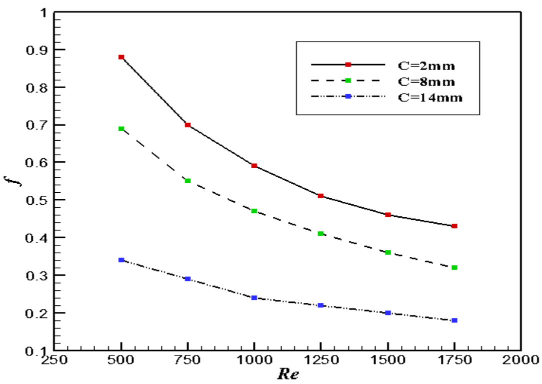

Figure 11. Friction factor in different Reynolds number

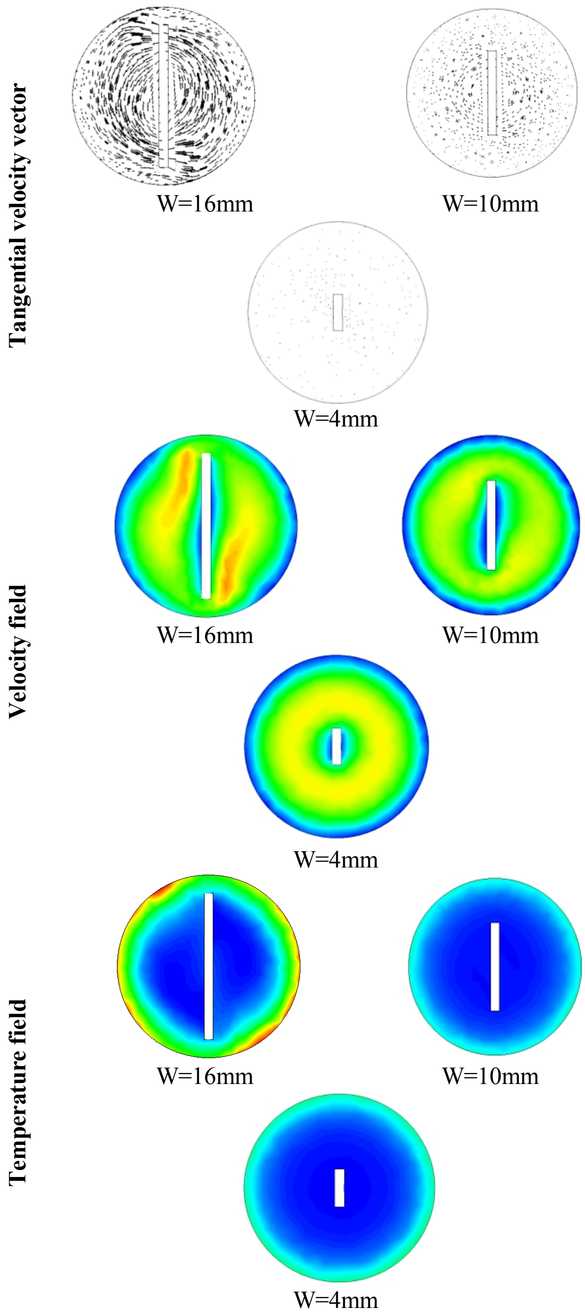

Figure 12. Plots of tangential velocity vector, velocity field and temperature field on cross sectional planes at L=0.25m

Observing tangential velocity vectors for three different w values it is understood that, lowering the width of the tapes not only makes near wall swirl disappeared, but also weakens the swirl in whole area. This can easily justify the reason why shortening the width from sides reduces thermal effectiveness of the tapes. Velocity and temperature contours shown in this figure also demonstrate that by shortening the tapes edge, the thermal boundary layer grows thicker, so temperature gradient near the wall becomes smaller.

These plots verify that for heat transfer enhancement technique, the boundary layer disturbance is a fundamental matter. Wholly, it can be said that, having tapes near the walls, disturbs the boundary layer better and this idea strengthens the technique of clearing the center of tapes instead of shortening them.

6. CONCLUDING REMARKS

In this effort, a circular tube equipped with twisted tape was numerically analyzed to see its thermo-hydraulic behavior and verify the influence of using short length twisted tapes and center cleared twisted tapes. The results represent that both techniques reduce the resistance for flowing fluid and improve the heat transfer by enhancing the flow Reynolds number. Comparing the amounts of the results for both techniques it is seen that cutting off the tapes edge weakens boundary layer disturbance and as a result heat transfer performance, while clearing the center of the tapes can enhance the thermal properties of the flow in a good way. Hence, for laminar convective heat transfer, using center cleared technique can be a promising idea.

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RESEARCH NOTE

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چکیده

این مقاله روشی عملی برای افزایش عملکرد حرارتی–سیالاتی لوله با مقطع دایروی ارائه می دهد. این روش، از رویکردی عددی با تمرکز بر جریان آرام درون لوله استفاده می کند تا بتواند به مقایسه تاثیر استفاده از نوارهای پیچیده شده از وسط خالی شده در اندازه های خاص در مقابل نوارهای ساده و مرسوم با عرض کوتاهتر بپردازد. تحلیل عددی نشان داده است که در هر دو حالت استفاده از نوارهای از وسط خالی شده و نوارهای ساده ی مرسوم با افزایش عدد رینولدز مقاومت مسیر سیال کاهش می یابد. مطالعه ی نوارهای با عرض کوتاه نشان داده است که با کاهش عرض نوار عملکردحرارتی و هیدرولیکی لوله مبدل کاهش می یابد. برخلاف آن با استفاده از نوارهای از وسط خالی شده با اندازه ی خاص در فضای خالی، می توان انتقال حرارت را افزایش داد. بنابراین استفاده از نوار پیچیده شده از وسط خالی شده در یک اندازه خاص می تواند بعنوان ایده ای عملی و مفید برای افزایش انتقال حرارت بشمار آید.

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