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Numerical analysis on enhanced performance of new coaxial cross twisted tapes for laminar convective heat transfer

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ABSTRACT

Owing to the high viscosity of lubricating oil, oil coolers meet the disadvantages of low heat transfer coefficients and thus large volumes. In order to enhance the heat transfer performance, a new type of twisted tape, called coaxial cross twisted tape, is proposed based on the field synergy theory and traditional twisted tapes. The numerical analysis of the heat transfer performance is presented in the article using CFD software STAR-CCM+. The local flow characteristics, and local and average convective heat transfer coefficients are analyzed, when the Reynolds number ranges from 40 to 1050. The effects of the four different twist ratios of 2.0, 3.0, 4.0 and ∞ on the heat transfer performance are also investigated. To evaluate the effect of heat transfer enhancement under given pumping power, the performance evaluation criterion (PEC) is discussed. The results indicate that the local convective heat transfer coefficient increases markedly with the insertion of the new twisted tapes because of the increase of the velocity near wall and thickness reduction of thermal boundary layer. The more flow zones are separated by the coaxial cross twisted tapes, the larger is the temperature gradient near wall and the higher is convective heat transfer coefficient. The Nusselt number and PEC of the heat transfer tube fitted with the new coaxial cross twisted tapes have increased by 151–195% and 90–123% of the traditional twisted tape, respectively.

1. Introduction

Oil coolers, which are widely used in many fields, such as power generation, chemical industry, metallurgy, steel production, refrigeration, and air-conditioning, are indispensable general heat exchangers. The main function of the oil coolers is to cool oil flowed through the bearings of steam turbines and pumps to a suitable temperature for the safe operation of steam turbines and pumps [1]. The highly-viscous oil generally leads to laminar or transition flows in tubes, and thus the main thermal resistance for the heat transfer processes lies in the highly-viscous oil side. It easily leads to poor heat transfer capability and large volume of oil coolers.

A large number of technologies of heat transfer enhancement are applied to achieve the purpose to improve energy efficiency [2–8]. However, enhanced technologies for oil coolers usually focus on the outside of heat transfer tubes or the shell side of oil coolers [9,10], which lead to some problems, such as pass-by flow among tubes. The pass-by flow counteracts the enhanced effects of enhanced heat transfer surfaces [10]. It is possible to avoid this problem and reduce the experimental cost, if oil flows inside tubes.

Owing to the advantages of easy replacement, convenient disassembly and assembly and eliminating dirt, the insertion of twisted tapes has been considered as a good enhancement technology for convective heat transfer in tubes, and has interested researchers to enhance the heat transfer of water in heat exchangers [11–17], as shown in Table 1. The experiment and simulation results show that different twisted tapes and their modified twisted tapes are effective devices to enhance laminar and turbulent convective heat transfer inside tubes.

In view of the good enhanced potential for laminar convective heat transfer, these twisted tapes and modified twisted tapes have been extended for highly-viscous fluid [18–24], as shown in Table 1. For example, Agarwal and Rao [18] carried out an experimental study to investigate the friction and heat transfer characteristics of twisted tapes for heating and cooling of servotherm oil under uniform wall temperature, and the twist ratios were from 2.41 to 4.84. The results showed that the *Nu* number at constant flow rate and constant pumping power were found to be 2.28–5.35 and 1.21–3.70 times of plain tube values, respectively.

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Nomenclature

C_p	specific heat capacity, kJ/(kg K)
D	diameter of the tube, mm
f	friction factor
h	convective heat transfer coefficient, W/(m^2 K)
L	test section length, m
Nu	Nusselt number
ΔP	pressure drop, Pa
PEC	performance evaluation criterion
Pr	Prandtl number
Q	amount of heat, W
ΔQ	difference between Q_o and Q_w, W
r	radius, m
Re	Reynolds number
Re_s	Reynolds number based on swirl velocity
T	temperature, °C
u	velocity, m/s
y	twist ratio

Greek letters

δ	thickness, m
θ	angle of the circumference, °
λ	heat conductivity, W/(m K)
μ	kinetic viscosity, Pa s
ν	dynamic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts

c	for the average
f	for the fluid
in	for the inlet
s	for the solid
o	for the oil
out	for the outlet
w	for the wall
0	for the plain tube

Saha et al. [19] investigated the pressure drop and heat transfer characteristics in a circular tube equipped with regularly spaced twisted tapes by experiments. The Prandtl number changed from 205 to 518. The regularly spaced twisted tapes with different rod diameters, tape widths and phase angles between successive tapes were used to produce swirl. The study concluded that the increase of phase angle between two successive tapes did not give effective results but increase manufacturing complexities.

Saha [20] carried out an experimental study on laminar flow in a circular duct having axial corrugation and equipped with center-cleared twisted tapes. The twist ratio of twisted tapes was 2.5. The working fluid used was Servotherm medium oil with the Prandtl number ranged from 320 to 545. The study concluded that the heat transfer coefficient was increased by 15–30% at constant pumping power.

Besides simple twisted tapes, many researchers have also investigated modified twisted tapes or compound enhanced methods based on twisted tapes. Saha [21] performed an experimental investigation on heat transfer and friction characteristics for laminar flow of viscous oil through a circular duct with integral helical ribs. The results showed that the use of both integral helical rib roughness and helical screw-tape inserts were better than the individual technique for heat transfer enhancement acting alone. New correlations were also developed for Nusselt number and friction factor. The developed correlations were fitted with experimental data within 13%.

Pal and Saha [22] carried out an experimental study to analyze heat transfer enhancement in a circular tube having integral spiral corrugation roughness and equipped with twisted tapes with oblique teeth. The experiments were performed for laminar flow of viscous oil and the twist ratios of the twisted tapes were 2.5 and 5. The results showed that the integral helical corrugated rough tube equipped with twisted tapes with oblique teeth gave better results for laminar flow.

Rout and Saha [23] carried out an experimental study on heat transfer and friction characteristics of laminar flow through a circular duct equipped with helical screw tapes and wire coil. Servotherm medium oil was used as working fluid and the range of Prandtl number was 228–552. It was found out that the performance of helical screw tapes with wire coil was better than either helical screw tapes or wire coil if used alone.

Saha [24] carried out an experimental investigation to study heat transfer and pressure drop characteristics of laminar flow through ducts having square and rectangular section with combined internal and axial corrugations on the duct surface and twisted tapes with or without oblique teeth. It was found that the performance of axial corrugations by using twisted tapes with or without oblique teeth was better than either twisted tapes or axial corrugations if used alone.

The mentioned literatures demonstrate that the extensive works for heat transfer in the tubes equipped with the traditional twisted tapes (TTTs) and some modified twisted tapes have been done by experiments and simulations. However, the structures of twisted tapes investigated are mainly based on TTTs, and few new types of twisted tapes are proposed. In the paper, a new type of twisted tape named coaxial cross twisted tape is presented according to the field synergy theory and its application for laminar convective heat transfer in tubes [25,26]. A numerical study on the heat transfer of lubricating oil through a tube with the new twisted tape inserted is reported based on CFD software STAR-CCM+.

The geometric structure of the coaxial cross twisted tapes and simulation model are presented in Section 2. The detail of the swirling flow induced by the coaxial cross twisted tapes and local convective heat transfer performance are analyzed in Section 3. Section 4 presents the influences of the twist ratio and the type of coaxial cross twisted tapes on oil-side heat transfer. In order to evaluate the performance of heat transfer enhancement of the new twisted tapes, the performance evaluation criterion is reported in Section 5.

2. Geometric structure and simulation model

2.1. Coaxial cross twisted tapes

On the basis of TTTs, combined with new processing technology like 3D printing, a new type of coaxial cross twisted tape is proposed. The new coaxial cross twisted tape includes coaxial cross double twisted tapes (CCDTTs) and coaxial cross triple twisted tapes (CCTTTs). They are formed by two or three pieces of twisted tapes with the same twist ratios and axes, respectively. The geometries of the coaxial cross twisted tapes and their cross sections are depicted in Fig. 1. The two pieces of twisted tapes for the CCDTT mutually forms an angle of 90°, and the CCTTT forms 60°.

Compared to the tubes inserted by the TTTs, lubricating oil flowing inside the tubes changes from two separated strands into