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Numerical Simulation of Forced Convection of Turbulent Nanofluids in a Twisted Elliptical Tube

Ching-Chi Wu*, Kuan-Hao Huang**, Yue-Tzu Yang*** and Cha`o-Kuang Chen***

Keywords: Mixture model; Nanofluid; Twisted elliptical tube; Heat transfer enhancement.

ABSTRACT

In this study, numerical calculations by the mixture model of turbulent Al_2O_3/water nanofluids forced convection in a three-dimensional twisted elliptical tube with constant wall temperature are investigated. Flow resistance and heat transfer characteristics of nanofluids in the twisted elliptical tube are studied with the parameters including Reynolds number, nanoparticle volume concentration, and the twist pitch. Effects of the parameters on the performance of the twisted elliptical tubes are analyzed and the overall thermal-hydraulic performance is evaluated in this study. The results show that the rotational motions are produced in the flowing nanofluid and could enhance the heat transfer performance in the twisted elliptical tubes compared with an oval tube. The average Nusselt number and the pressure drop both increase with the increasing of Reynolds number and nanoparticle volume concentration, but both decrease with the increasing of the twist pitch.

INTRODUCTION

Tube heat exchangers are widely used in engineering applications. The efficient of the tube heat exchanger can be promoted by enhancing the heat transfer in the tube. In this study, two methods are concerned to improve the thermal performance of tube heat exchangers, i.e., changing the shape of the cross section and the properties of the working fluid. The twist elliptical tube is one of the heat transfer enhancement tube, and it only has been studied by a few researchers (Asmantas et al., 1985; Meng et al., 2005; Tan et al., 2013; Yang et al., 2011; Tan et al., 2012; Zhang et al., 2012). Asmantas et al. (1985) presented the experimental results of the heat transfer and flow resistance characteristics of turbulent air flowing through twisted elliptical tubes with different twisted pitches (d). The results showed the average Nusselt number and the flow resistant increased as d decreased. The heat transfer was augmented by 40% when $L/d = 6.2$, and the average hydraulic drag also increased by 70% on the average.

Other researches were carried out with different geometrics, working fluids and Reynolds numbers. Si and Xia (1995) used turbulent diesel fuel as working fluid and indicated that it was the vortex in the twisted elliptical tubes promoting heat transfer. Zhang et al. (2007) studied the flow in different aspect ratio and demonstrated that the heat transfer coefficient and the friction factor increased as the aspect ratio increased. Yang and Li (2003) studied the heat transfer of fluid with different Prandtl number in laminar flow region. And the results showed that the thermal-hydraulic performance was better when the Prandtl number was greater. Yang et al. (2011) conducted a research on the heat transfer and flow characteristics of water flow in the twisted elliptical tubes in laminar, transition and turbulent regions. Correlations of the average Nusselt number and the friction factor were derived. It was discovered that the heat transfer performance was better in the laminar flow region.

As for changing the properties of the working fluid, nanofluids have attracted the interests of many researchers because of the marked enhancement in the thermal transport properties. Nanofluids are composed of basic fluid and nanoparticles. The high thermal conductivity coefficient of the solid particles improves the heat transfer ability of the basic fluid. Nanofluid was proposed by Choi (1995) firstly in 1995,

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** Graduate Student, Department of Mechanical Engineering, National Cheng Kung University, Tainan, 70101, Taiwan, ROC.*

*** PhD Candidate, Department of Mechanical Engineering, National Cheng Kung University, Tainan, 70101, Taiwan, ROC.*

**** Professor, Department of Mechanical Engineering, National Cheng Kung University, Tainan, 70101, Taiwan, ROC..*

indicating that the heat transfer of nanofluid was greater than that of the basic fluid. Lee et al. (1999) used the nanoparticles of Al_2O_3 and CuO and chose water and ethylene glycol as the basic fluids. The results demonstrated that Cuo/EG nanofluid had the greatest heat transfer performance, and the increase was around 20% when the volumetric concentration was 4%. Keblinski et al. (2002) pointed out the explanations for the anomalous increase in heat transfer including Brownian motion of the particles, molecular-level layering of the liquid at the liquid/particle interface, the nature of heat transport in the nanoparticles, and the effects of nanoparticle clustering. Due to the relative velocity between basic fluid and nanoparticles, multi-phase model is more accurate than single-phase model. Akbari et al. (2011) compared the thermal characteristics and flow field with single-phase model and two-phase models. It was found that single-phase and two-phase models predicted almost identical flow fields but very different in thermal characteristics. The results of two-phase models were more consistent with experimental results. Therefore, in the present study, we focus on multi-phase approach.

Furthermore, we have conducted the research on the numerical simulation of turbulent flow forced convection in a twisted elliptical tube in the previous study (Wu et al., 2018). In this study, numerical calculations by the mixture model of turbulent Al_2O_3/water nanofluids forced convection in a three-dimensional twisted elliptical tube with constant wall temperature are investigated. The steady-state, three-dimensional governing equations for forced convection of Al_2O_3/water nanofluids are solved numerically using the finite volume approach. Flow resistance and heat transfer characteristics of nanofluids in the twisted elliptical tube are studied with the parameters including Reynolds number ($10000 \le Re \le 15000$), nanoparticle volume concentration ($0\% \le \phi \le 4\%$), and the twist pitch ($96\ mm \le d \le 192\ mm$).

NUMERICAL SCHEME

Physical model

The main geometrical parameters of the twisted elliptical tubes are as follows: the major axis (a = 11.18 mm), the minor axis (b = 5.2 mm) of the cross section, the tube length (L = 768 mm), and the twist pitch (d). Besides, the dimension of the cross section and the tube length are fixed in the present study. And the range of 360° twist pitches of the twisted elliptical tubes investigated in the study is from 96 mm to 192 mm. The physical model is as shown in Figure 1. The flow is described in a coordinate system (x, y, z) in which the flow direction is z-direction.

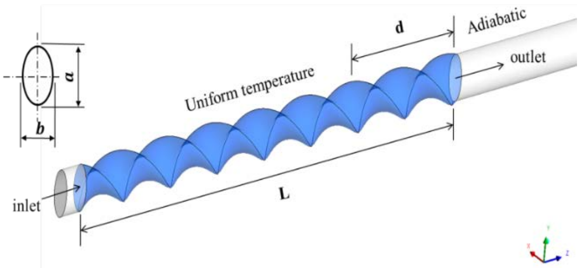

Figure 1. Physical model of a twisted elliptical tube with constant wall temperature in this study

Physical properties

The physical properties, density ρ_{nf} and specific heat capacity Cp_{nf} of Al_2O_3/water nanofluids are calculated using mixing theory, presented as:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_p \tag{1}$$

$$Cp_{nf} = (1-\phi)Cp_{bf} + \phi Cp_p \tag{2}$$

The effective thermal conductivity coefficient λ_{nf} and viscosity μ_{nf} of Al_2O_3/water nanofluids are given by Maïga et al. (2004), presented as follows:

$$\lambda_{nf} = (4.97\phi^2 + 2.72\phi + 1)k_{bf} \tag{3}$$

$$\mu_{nf} = (123\phi^2 + 7.3\phi + 1)\mu_{bf} \tag{4}$$

The material properties of Al_2O_3 nanoparticles are set to be constant and as shown in Table 1.

Table 1 Material properties for Al_2O_3 nanoparticles

	$\rho_p\,(kg/m^3)$	$Cp_p\ (J/kg\cdot K)$	$\mu_p\,(kg\cdot m/s)$	$\lambda_p\ (W/m\cdot K)$
Al_2O_3	3880	773	-	36

Governing equations

The three-dimensional governing equations of the flow for the mixture model are presented with the following basic assumptions:

(1) The flow is considered to be steady state, continuous, and turbulent flow.
(2) The nanofluids are incompressible dilute mixtures with constant properties.
(3) Viscous dissipation and radiation effect are negligible.
(4) Nanoparticles are spherical and uniform in size.

Therefore, the resulting governing equations are shown as follows:

Continuity equation:

$$\nabla \cdot \rho_m V_m = 0 \tag{5}$$

Momentum equation:

$$\nabla\cdot(\rho_m V_m V_m) = -\nabla p_m + \nabla\cdot(\mu_m \nabla V_m + (1-\phi)\rho_{bf} V_{bf} V_{bf} + \phi\rho_p V_p V_p) + \nabla\cdot\left[(1-\phi)\rho_{bf} V_{dr,bf} V_{dr,bf} + \phi\rho_p V_{dr,p} V_{dr,p}\right] \quad (6)$$

Energy equation:

$$\nabla\cdot(\phi_k V_k \rho_k h_k) = \nabla\cdot(\lambda_m \nabla T) \quad (7)$$

Volume concentration equation:

$$\nabla\cdot(\phi_p V_m) = -\nabla\cdot(\phi_p \phi_f \frac{\rho_p}{\rho_m} V_{pf}) \quad (8)$$

where ρ_m, V_m, μ_m and λ_m are the mixture density, velocity, viscosity and thermal conductivity coefficient of nanofluids respectively, and that can be defined as:

$$\rho_m = \sum_{k=1}^{n} \phi_k \rho_k \quad (9)$$

$$V_m = \frac{1}{\rho_m}\sum_{k=1}^{n} \phi_k \rho_k V_k \quad (10)$$

$$\mu_m = \sum_{k=1}^{n} \phi_k \mu_k \quad (11)$$

$$\lambda_m = \sum_{k=1}^{n} \phi_k \lambda_k \quad (12)$$

The drift velocity $V_{dr,bf}$, $V_{dr,p}$ are defined as the velocity of the phase (fluid, solid) relative to the mixture:

$$V_{dr,p} = V_p - V_m \quad (13)$$

$$V_{dr,bf} = V_{bf} - V_m \quad (14)$$

The relative velocity V_{pf} is defined as the velocity of the secondary phase (solid, *p*) relative to the primary phase (fluid, *f*):

$$V_{pf} = V_p - V_f \quad (15)$$

The calculations of the relative velocity V_{pf} and the drag function f_{drag} are given by Manninen et al. (1996) and Shiller and Naumann (1935):

$$V_{pf} = \frac{\tau_p {d_p}^2}{18\mu_f f_{drag}} \frac{(\rho_p - \rho_m)}{\rho_p} \vec{a} \quad (16)$$

$$f_{drag} = \begin{cases} 1 + 0.15\,\mathrm{Re}_p^{0.687} & \mathrm{Re}_p \le 1000 \\ 0.0183\,\mathrm{Re}_p & \mathrm{Re}_p > 1000 \end{cases} \quad (17)$$

where d_p is the diameter of the nanoparticles. The particle relaxation time τ_p and the acceleration of the secondary phase particle $\vec{a}$ is defined as:

$$\tau_p = \frac{\rho_p {d_p}^2}{18\mu_f} \quad (18)$$

$$\vec{a} = \vec{g} - (V_m\cdot\nabla)V_m \quad (19)$$

In the calculation of the Reynolds number of nanoparticles Re_p, the viscosity of nanoparticles is given by Miller and Gidaspow (1992):

$$\mu_p = -0.188 + 537.42\phi \quad (20)$$

Turbulent model

An appropriate turbulent model is required to solve the closure problem, and the standard $k-\omega$ model proposed by Wilcox (2008) is applied in this study and it has been modified to confirm the presence of nanoparticles.

The standard $k-\omega$ model can be expressed with two equations, one for turbulent kinetic energy, k, and the other for the specific dissipation rate, ω. The equations are defined as follows:

$$\nabla\cdot(\rho_m V_m k) = \nabla\cdot[(\mu_{l,m} + \frac{\mu_{t,m}}{\sigma_k})\nabla k] + \mu_{t,m}\nabla V_m\cdot(\nabla V_m + \nabla V_m^T) - \rho_m k\omega \quad (21)$$

$$\nabla\cdot(\rho_m V_m \omega) = \nabla\cdot[(\mu_{l,m} + \frac{\mu_{t,m}}{\sigma_\omega})\nabla \omega] + C_1\omega\mu_{t,m}\nabla V_m\cdot(\nabla V_m + \nabla {V_m}^T) - C_2\rho_m k\omega^2 \quad (22)$$

where σ_k and σ_ω represent the turbulent Prandtl number for turbulent kinetic energy and specific dissipation rate, respectively. The turbulent viscosity $\mu_{t,m}$ is defined as:

$$\mu_{t,m} = C_\mu f_\mu \rho_m \frac{k}{\omega} \quad (23)$$

where f_μ is the damping function for turbulence model:

$$f_\mu = \exp[\frac{-3.4}{(1+\mathrm{Re}_t/50)^2}] \quad (24)$$

The local turbulent Reynolds number Re_t can be obtained by:

$$\mathrm{Re}_t = \frac{\rho_m k}{\mu_m \omega} \quad (25)$$

The model constants in the study are shown as below:

$$C_\mu = 0.09,\ C_1 = 0.511,\ C_2 = 0.833 \quad \sigma_k = 2.0,\ \sigma_\omega = 2.0 \quad (26)$$

Boundary conditions

The problem under consideration is turbulent flow in a twisted elliptical tube. The flow direction is z-direction, and the fluid enters with a uniform inlet velocity w_{in}, which varies according to Reynolds number and the concentration of the nanoparticles. The inlet temperature is constant, $T_{in} = 330$ K . In the test section, i.e. the twisted elliptical tube, no-slip condition and constant temperature, $T_w = 300$ K , are imposed on the wall. In the entrance section and the exit section, i.e. the oval tube, no-slip and adiabatic conditions are imposed on the wall. Moreover, turbulent kinetic energy and the specific dissipation rate are set to be zero in correspondence of the wall. At the outlet, the flow is fully developed, and the pressure is set equal to 1 atm.

RESULTS AND DISCUSSION

Grid independence and validation

This study is to simulate the fluid flow and heat transfer in the twisted elliptical tubes by using the commercial computational fluid dynamics (CFD) software ANSYS FLUENT v.15 and the SIMPLE algorithm is used to solve the Navier-Stokes equations. The calculations of data are all according to the chosen calculations in Yang et al. (2011).

Grid independent and validation are done to ensure the accuracy of the numerical results. Three different grid numbers have been constructed and tested with the twist pitch $d = 192$ mm , the concentration of nanoparticles $\phi = 2$ % and Reynolds number $\mathrm{Re} = 12000$ to identify an appropriate mesh number to achieve grid independence. The result of the grid independent test is shown in Table 2. One can see that the difference between the averaged Nusselt numbers obtained from the medium mesh and the finest mesh is less than 1 %, indicating that the medium mesh with the grid number = 993470 is fine enough to ensure a grid independent solution.

Table 2. The results of the grid independent test

Grid number	$\overline{Nu}$	difference
1404400	197.3	-
993470	196.5	0.4%
755398	194.0	1.7%

Due to the lack of investigations into nanofluids flowing through a twisted elliptical tube, the averaged Nusselt number obtained from the present study is compared with the experimental results of Yang et al. (2011) with the pure water and Reynolds number ranging from 5000 to 27000. The geometrical parameters are the same values that are used by Yang et al. (2011). Among the validation, the maximum derivation of the averaged Nusselt number is less than 4%, demonstrating that the present calculations are in good agreement with the experimental results. Also, the exit length is tested to ensure that the flow is fully developed at the outlet in corresponding to the boundary condition.

Flow field characteristics

Figure 2 shows the distributions of velocity and streamlines in twisted elliptical tubes. In the oval tube, the streamlines are like the straight circular tube in axis-direction, and the velocity at the center of the tube is larger than the velocity near the wall because of the wall shear stress. In contrast, because the flow direction is affected by the twisted tube wall, the streamlines are spiral near the tube wall in the twisted elliptical tubes. Besides, the presence of the secondary flow result from rotational motions that is mixing the nanofluids and destroying the boundary layer. The intensity of the second flow increases with decrease in the twist pitch, d.

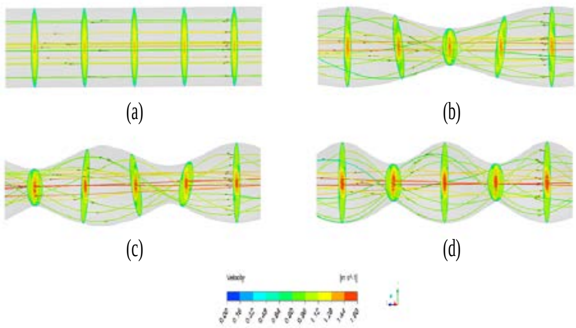

Figure 2. The velocity and streamlines distributions with $\phi = 2\%$ and $\mathrm{Re} = 12000$, when (a) oval tube; (b) $d = 192$ mm ; (c) $d = 128$ mm ; (d) $d = 96$ mm

The local velocity distributions at the center of twisted elliptical tubes with different twist pitches is as shown in Figure 3. The velocity of the tube increases with decrease in the pitch length at the center. In the cross sections, the dramatic variation in velocity causes the enhancement of the pressure drop. For the concentration, $\phi = 2\%$, the average pressure drop increase of the twisted elliptical tube with $d = 96$ mm remains around 60% compared with the oval tube for Re numbers ranging from 10000 to 15000.

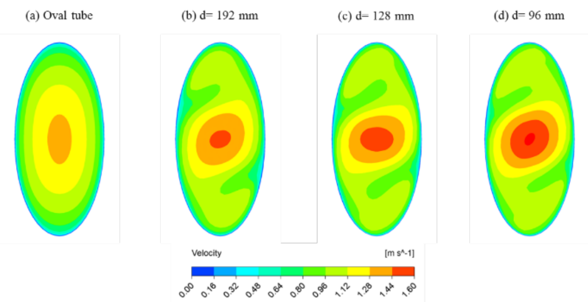

Figure 3. The local velocity contours at cross sections with $\phi = 2\%$ and $\mathrm{Re} = 12000$, when (a) oval tube; (b) $d = 192$ mm ; (c) $d = 128$ mm ; (d) $d = 96$ mm

In addition, nanofluids also enhance the pressure drop because of the higher viscosity. In comparison with water, for $d = 128$ mm, the average pressure drop increase with $\phi = 4\%$ and remain around 70% for Re numbers ranging from 10000 to 15000. In conclusion, the pressure drop increase with the decrease of the twist pitch and increase in the volumetric concentration of nanoparticles.

Heat transfer characteristics

Figure 4 demonstrates the local temperature distributions of twisted elliptical tubes with different twist pitches at the center. Secondary flow caused by the twisted wall brings the hot flow at the center to the low-temperature wall, promoting in heat transfer. The results show that the temperature distributions are similar to its velocity distributions. Besides, the temperature decreases in the cross section of the tube and the average Nusselt number increases as the pitch length decreases. For $\phi = 2\%$, the average Nusselt number ($\overline{Nu}$) increases in the twisted elliptical tube with $d = 128$ mm and remains around 28% compared with the oval tube for Re numbers ranging from 10000 to 15000.

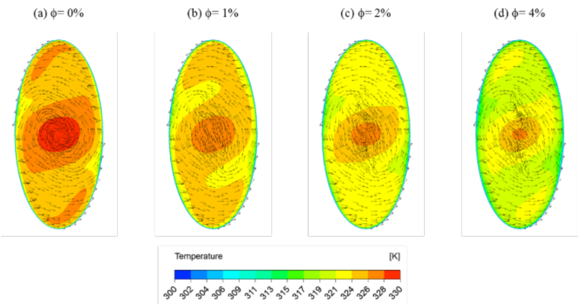

Figure 4. The local temperature contours and velocity vectors at cross sections with $\phi = 2\%$ and $Re = 12000$, when (a) oval tube; (b) $d = 192$ mm; (c) $d = 128$ mm; (d) $d = 96$ mm

Figure 5 illustrates the local temperature distributions at the center of twisted elliptical tubes with different concentrations. As the concentration of nanoparticles rises, the local temperature decreases dramatically because the higher thermal conductivity coefficient promotes the heat transfer ability of the fluid. The impact of the concentration exceeds that of the twist pitch. For $d = 128$ mm, the average Nusselt number increases with $\phi = 4\%$ and remains around 200% compared with pure water for Re numbers ranging from 10000 to 15000. To sum up, the impact of concentration on the heat transfer is greater than that of the twist pitch.

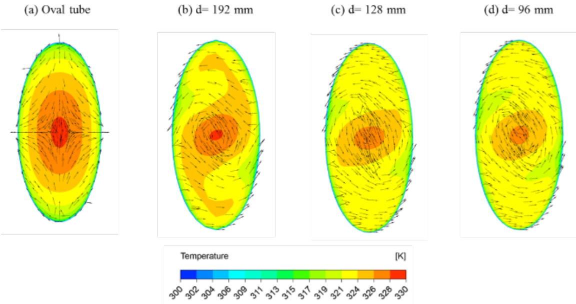

Figure 5. The local temperature contours and velocity vectors at cross sections with $d = 128$ mm and $Re = 12000$, when (a) $\phi = 0\%$; (b) $\phi = 1\%$; (c) $\phi = 2\%$; (d) $\phi = 4\%$

The overall thermal-hydraulic performances, E_0 and E_{pw}, are calculated in this study. Despite of the high pressure drop, E_0 increases with the decrease of the twist pitch. For $\phi = 2\%$, E_0 of the twisted elliptical tube with $d = 128$ mm remains around 1.07 for Re numbers ranging from 10000 to 15000. For $d = 128$ mm, E_{pw} with $\phi = 4\%$ remains around 2.5 for Re numbers ranging from 10000 to 15000.

CONCLUSIONS

In this research, a numerical approach has been investigated for obtaining the pressure drop and heat transfer characteristics of the twist elliptical tube. The effects of the parameters including geometrical parameter, d, and physical property of the fluid, ϕ, are investigated based on the results. The major findings are summarized as follows:

(1) The twist elliptical tubes bring on the pressure drop because of the twisted wall. But the twist elliptical tubes can enhance heat transfer. $\overline{Nu}$ with $d = 96$ mm increases 16% – 26% compared with the oval tube. E_0 increases with the decrease of d and an increase of ϕ.

(2) The pressure drop increase with the higher concentration because of the high viscosity of Al_2O_3 nanoparticles. Despite this, the high thermal conductivity coefficient of nanoparticles promotes the heat transfer ability of the fluid. $\overline{Nu}$ with $\phi = 4\%$ increases 182% – 205% compared with the results of water. E_{pw} increases with the decrease of d and an increase of ϕ.

(3) Both the twist pitch and the concentration of nanofluid can promote thermal-hydraulic performances, and the results show that the concentration of nanofluid have more influence than the twist pitch. Moreover, the increase of E_{pw} increases as d decreases, indicating that nanofluids are more effective in the twisted

elliptical tubes than in the oval tube.

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CONFLICTS OF INTEREST

The authors declare that there is no actual or potential conflict of interest regarding the publication of this article.

NOMENCLATURE

a Major axis of the elliptical tubes
b Minor axis of the elliptical tubes
Cp Specific heat capacity
Dh Hydraulic diameter of the elliptical tubes
d 360° Twist pitch of the twisted elliptical tubes
E_0 The overall thermal-hydraulic performance with respect to the oval tube ($E_0 = \left(\overline{Nu}/\overline{Nu}_0\right)\left(\Delta p/\Delta p_0\right)^{-\frac{1}{3}}$)
E_{pw} The overall thermal-hydraulic performance with respect to water ($E_{pw} = \left(\overline{Nu}/\overline{Nu}_w\right)\left(\Delta p/\Delta p_w\right)^{-\frac{1}{3}}$)
h Convective heat transfer coefficient
k Turbulence kinetic energy
L Length of the twisted elliptical tubes
$\overline{Nu}$ The average Nusselt number ($\overline{Nu} = hD_h / \lambda$)
p Pressure
Re Reynolds number
T Temperature
u, v, w Velocity components
V Velocity vector
z Axial coordinate

Greek symbols

ρ Density
μ Viscosity
ϕ Volumetric concentration of nanoparticles
λ Thermal conduction coefficient
ω Specific dissipation rate

Subscripts

bf Basic fluid
f Fluid
m Mixture
nf Nanofluid
p Nanoparticle
pw Pure water
t Turbulent
w Wall
0 Oval tube

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扭曲橢圓管內紊流奈米流體的強制對流之數值模擬

吳靖琪　黃冠豪　楊玉姿　陳朝光

國立成功大學機械工程學系

摘 要

本文以兩相模型模擬奈米流體於均勻等壁溫三維扭曲橢圓管紊流強制對流之數值計算。利用雷諾數、奈米粒子體積濃度和扭曲等參數，研究了扭曲橢圓管中奈米流體的流動阻力和傳熱特性。並分析該參數對扭曲橢圓管性能的影響，以及評估了整體熱工水力性能。模擬結果顯示與橢圓直管相比，奈米流體流經扭曲橢圓管所產生之旋轉，會使得熱傳性能之增強。且扭曲橢圓管之平均紐賽數與壓降，會隨著雷諾數與奈米粒子體積濃度增加而增加，並隨著節距長度增加而減少。