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CFD Simulation of Heat Transfer in a Corrugated and Baffled Tube Exchanger

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Abstract

Heat transfer enhancement in heat exchangers is a current topic in thermal engineering. Common enhancement methods include nanofluids, modified channel geometry, porous media, and baffles. The novelty of this work is the simultaneous use of a wavy wall and a central baffle to disturb the flow field, combined with a water–titanium oxide nanofluid. The aim is to investigate, by computational fluid dynamics, the effects of Reynolds number, wall wavelength, and nanoparticle volume fraction on heat transfer under laminar, steady, and continuous flow. Two-dimensional simulations were performed in Ansys CFX 2023R1. Results show that in the corrugated and baffled channel, a lower nanoparticle concentration (φ = 0), a higher flow velocity (Re = 500), and a shorter wall wavelength (λ = 12 mm) yield the largest Nusselt number.

Keywords :

Numerical study, Nusselt number, baffle, wavy wall, nanofluid

1. Introduction

Heat transfer enhancement is of great importance in industrial equipment such as radiators, boilers, and heat exchangers. Several techniques have been proposed, including improved working fluids (nanofluids), increased heat transfer area, and modified channel geometry. Adding solid particles at millimeter and micrometer scales increases thermal conductivity but causes poor stability, erosion, and high pressure drop; reducing particle size to the nanoscale increases conductivity while lowering pressure drop [1]. However, some studies report a reduction in heat transfer with nanofluids [2, 3]. Numerous works have examined nanofluids [4], channel cross-section geometry [2, 5], wall geometry [6], ribs [7], and baffles [8]. Researchers have also studied extended surfaces [9], flexible walls [10], and shell-and-tube redesign [11].

A review of the literature shows that the combined effect of a wavy wall and a central baffle on heat transfer in a heat exchanger has not been clarified. Therefore, the novelty of this research is the use of a baffle in the middle of a channel with a wavy wall to change the flow lines and disturb the fluid. The aim is to model a two-dimensional tube to investigate the heat transfer behavior of a water–TiO_2 nanofluid and to identify the conditions giving the maximum heat transfer, considering the effects of wall geometry, nanoparticle concentration, and Reynolds number on temperature and velocity distributions.

2. Methodology

2. Methodology

Ansys CFX 2023R1 was used for the two-dimensional simulation. Nanofluid density and specific heat were obtained from Eqs. (1) and (2), viscosity from Eq. (3), and thermal conductivity from Maxwell's relation, Eq. (4) [12, 13]:

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_P \quad (1)$$

$$(\rho C_P)_{nf} = (1-\varphi)(\rho C_P) + \varphi(\rho C_P)_P \quad (2)$$

$$\mu_{eff} = (1 + 3.544\varphi_P + 169.46\varphi_P^2)\mu_f, \quad 0 \le \varphi_P \le 0.9 \quad (3)$$

$$\frac{k_{nf}}{k_f} = \frac{2k_p + k_f + \varphi(k_P + k_f)}{2k_p + k_f - \varphi(k_P + k_f)} \quad (4)$$

The flow was assumed laminar, steady, two-dimensional, incompressible, and continuous, with homogeneous nanofluid properties. The governing equations are continuity, momentum, and energy [14]:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (5)$$

$$\rho(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}) = -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}) \quad (6)$$

$$\rho(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}) = -\frac{\partial p}{\partial y} + \mu(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}) \quad (7)$$

$$\rho c_P(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}) = k(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) \quad (8)$$

Table 1. Thermophysical properties of water and TiO_2 [15]

Fluid	ρ (kg/m³)	C_p (J/kg·K)	k (W/m·K)
Water	997.1	4179	0.613
TiO_2	4250	686.2	8.95

Table 2 gives the channel dimensions. We added an upstream flat section to improve convergence and used a boundary-layer mesh near the walls, where velocity and temperature gradients are high. At the inlet, a uniform velocity corresponding to Re = 100, 300, and 500 and a temperature of 300 K were imposed; at the outlet, a relative pressure of 0 Pa was specified. No-slip and no-temperature-jump conditions were applied on the walls. A mesh-independence study at λ = 36 mm, Re = 500, and pure water showed that above 160,000 elements the average Nusselt number changed by less than 2%, so 160,000 elements were used with a convergence criterion of 10^{-6}. Validation against Habibi and Salimpour [16] at Re = 150 showed a deviation of less than 4.6% in the local Nusselt number distribution along the channel.

Table 2. Geometric dimensions of the channel

H (mm)	L (mm)	λ (mm)	a_1 (mm)	a_2 (mm)	a_3 (mm)
10	350	12, 24, 36	3	3	30

3. Results and Discussion

Temperature and velocity contours are shown in Figure 1 for different concentrations at λ = 12 mm and Re = 100. Increasing φ from 0 to 0.04 increased the maximum velocity from 1.43 to 1.45 cm/s (about 1.4%), while the temperature contours were essentially unchanged, with the maximum temperature near the wall equal to 310 K. This agrees with reports that water–TiO_2 has lower heat transfer performance than water–Al_2O_3 [17] and that the Nusselt number decreases with increasing volume fraction [3]. Increasing Re from 100 to 500 raised the maximum velocity from 1.43 to 7.13 cm/s (about fourfold) and made the temperature distribution more uniform in the wavy region, indicating better convection. Increasing λ from 12 to 36 mm reduced the maximum velocity near the baffle from 7.13 to 5.57 cm/s (about 22%), while the flow approached the wavy wall more closely.

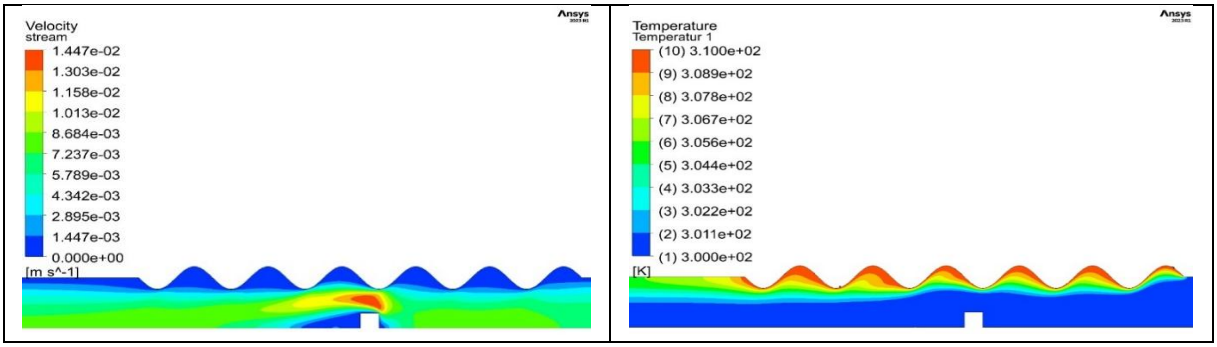


Figure 1. Temperature and velocity contours for φ = 0.04 at λ = 12 mm and Re = 100

The distribution of the Nusselt number versus Reynolds number for different concentrations and wavelengths is shown in Figure 2. The Nusselt number increased with Reynolds number for all concentrations; the effect of Re was weaker at higher concentrations. Increasing the concentration reduced Nu, and this effect became more pronounced at high Re: at φ = 0, Nu decreased by about 0.5%, and at φ = 0.04 by about 8%. Increasing λ from 12 to 36 mm reduced the average Nusselt number from 21 to 14 (about 33%). The largest increase in Nu (81%) occurred at λ = 12 mm and φ = 0. These findings are consistent with [2], while [6] reported enhancement with water–Al_2O_3.

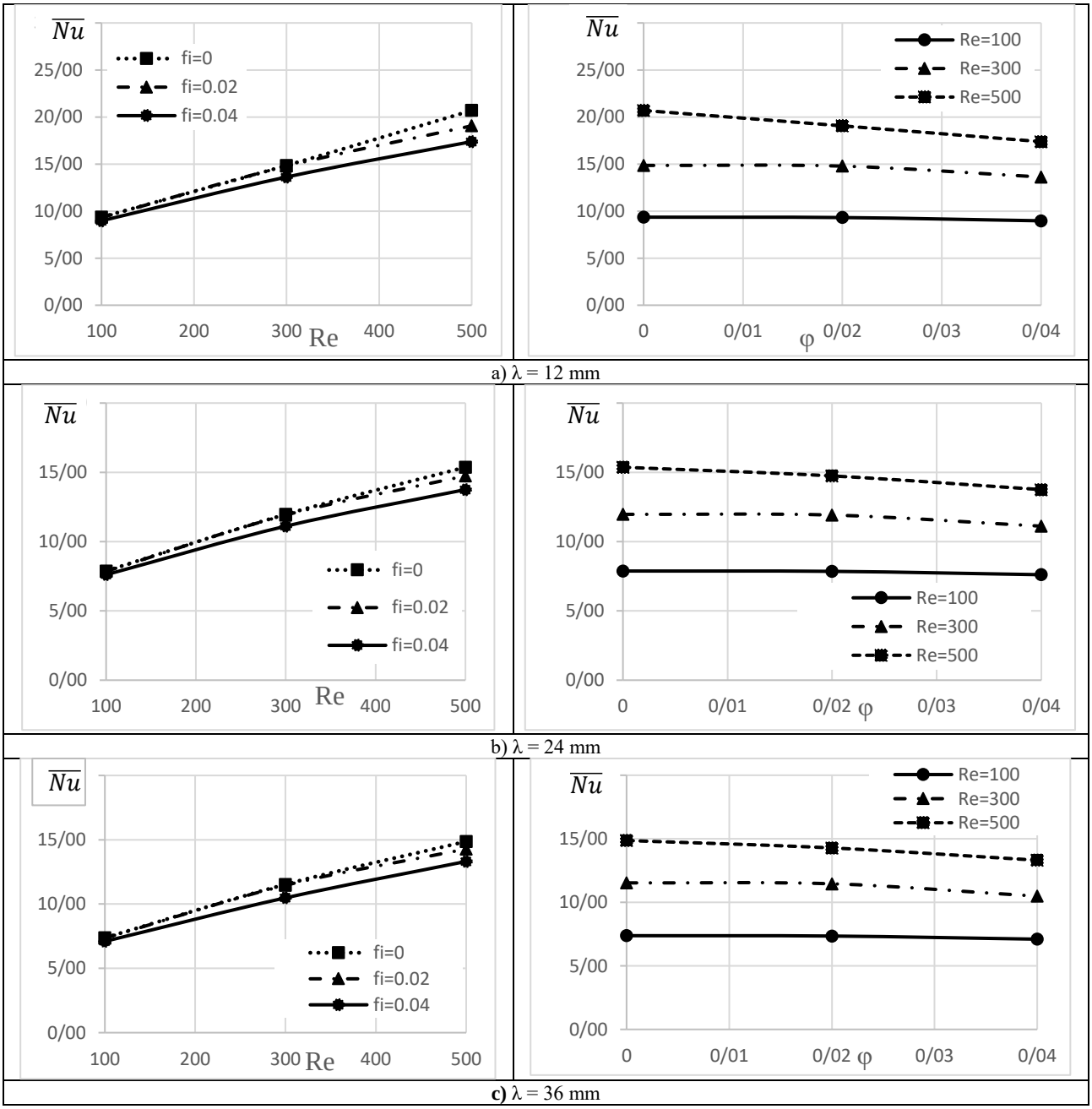


Figure 2. Average Nusselt number versus Reynolds number for different nanofluid concentrations at (a) λ = 12 mm, (b) λ = 24 mm, and (c) λ = 36 mm

4. Conclusions

In the corrugated and baffled channel, increasing the water–TiO_2 volume fraction reduced the Nusselt number; the maximum reduction was 8% at Re = 500 and φ = 0.04. Increasing the wavelength from 12 to 36 mm reduced the average Nusselt number from 21 to 14 (about 33%). Increasing the Reynolds number increased the average Nusselt number, with a maximum increase of 81% at λ = 12 mm and φ = 0. Therefore, to achieve the largest Nusselt number (i.e., more active convective heat transfer) in a corrugated and baffled channel, a lower nanofluid concentration (φ = 0), a higher flow velocity (Re = 500), and a shorter wavelength (λ = 12 mm) should be used.

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