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A sensitivity analysis on thermal and pumping power for the flow of nanofluid inside a wavy channel

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ABSTRACT

In this study, a sensitivity analysis is performed by means of surface methodology in order to manage thermal and pumping power for nanofluid flow inside a wavy channel. The governing equations such as 2D steady continuity, momentum, and energy equations have been solved using a finite volume approach. The computational simulations are performed for different Reynolds number ($300 \le Re \le 600$), solid volume fractions of nanoparticles ($0.01 \le \varphi \le 0.05$) and channel aspect ratio. The average Nusselt number and the pressure drop ratio are also calculated by numerical experimentation. It was found that the mixing of fluid in wavy channel improves, consequently, the temperature gradient near the wall increases by increasing the amplitude of the wavy wall. The maximum enhancement in Nusselt number with increase in aspect ratio ($\lambda = 0.1 \rightarrow 0.3$) is in the vicinity of 56% for $Re = 600$ and $\varphi = 1\%$, while it is in the vicinity of 24% due to increase in the solid volume fraction ($\varphi = 1\% \rightarrow 5\%$)for $Re = 600$ and $\lambda = 0.1$. Moreover, the non-dimensional pressure drop is more sensitive to the channel aspect ratio rather than the Reynolds number and solid volume fraction. Besides, the sensitivities of average Nusselt number to the Reynolds number and channel aspect ratio increase with increase in the channel aspect ratio.

1. Introduction

The study of the fluid flow and heat transfer inside a channel has received many attentions due to its numerous applications such as cooling devices in automotive, heat exchanger systems, heat sinks for electronic components, cooling towers, aerospace industries, oil and gas flow in reservoirs, chemical processing, hydrocarbon processing, polymers, pharmaceuticals, etc. In most of said applications, improving the heat transfer rate has been of great interest of theoretical and experimental builders. The corrugated wall of a channel and adding the nanoparticles to the base fluid are two usual techniques to improve the heat transfer rate. Beside positive outcome, these techniques have also negative impact on the pressure drop or powering cost. Due to this reason, a sensitivity analysis is crucial from the viewpoint of energy management for such technological to determine how much changes in governing variables will change the heat transfer rate and powering cost [1]. The results of this analysis can be utilized at design decisions by engineers for mentioned applications. Some researchers have studied the fluid flow and heat transfer inside a wavy channel numerically and experimentally. Laminar flow and heat transfer in a corrugated duct was studied numerically by Asako and Faghri [2]. They found that the heat transfer rate in a sinusoidal channel was in the vicinity of 40% larger than that for the flat plates channel under similar conditions. Wang and Chen [3] studied the forced convection heat transfer inside a wavy channel by using simple coordinate transformation method. They observed the crests of Nusselt number and skin-friction coefficient near the peak of the wavy wall. Moreover, the minimum quantities of these parameters were placed upstream and downstream within a short space from the maximum section of each wave. Rush et al. [4] investigated experimentally the flow and heat transfer in sinusoidal wavy passages. They observed a direct effect of the channel geometry on the local Nusselt number. Heidary and Kermani [5] investigated numerically the nanofluid forced convection flow in a sinusoidal-wall channel. They reported that the heat transfer between the sinusoidal wall and the core flow was strongly depended on the amplitudes of wavy wall. Further, they observed a 50% increase in heat transfer rate by addition of nanoparticles to the base fluid and applying the wavy walls. Rashidi et al. [6] performed a numerical study on the nanofluid heat transfer in wavy channel. They used the single and two-phase approaches to simulate the nanofluid. They witnessed an increase in the skin friction coefficient with an increase in the Reynolds number for all models. Ahmed et al. [7] enhanced the heat transfer rate inside a wavy channel by using nanofluid. Their results indicated that the increment in heat transfer rate depends on the solid volume fraction of nanoparticle, Reynolds

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Nomenclature

a	wave amplitude (m)
ANOVA	analysis of variance (–)
C	specific heat (J/kg K)
CCD	central composite design (–)
CCF	central composite face centered (–)
CFD	computational fluid dynamics (–)
DOE	design of experiments (–)
d_f	molecular diameter of base fluid (nm)
d_p	nanoparticle diameter (nm)
f	number of factors (–)
H	half separation distance between wavy walls (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity of fluid (W/m K)
L	length of the channel (m)
L_w	wavelength of the wavy wall (m)
l_{BF}	mean free path of water (–)
Nu	Nusselt number (–)
Nu_{ave}	average Nusselt number (–)
Pr	Prandtl number ($=\upsilon_f / \alpha_f$) (–)
ΔP^*	pressure drop (Pa)
ΔP	dimensionless pressure drop ($\Delta P = \frac{\Delta P^*}{\rho {U_m}^2}$)
Re	Reynolds number ($= \frac{\rho_f U_m H}{\mu_f}$) (–)
Res	response (–)
RSM	response surface methodology (–)
T	temperature (K)
U_m	average velocity in channel (m s^{-1})
u, v	velocity component in x and y directions (m s^{-1})
x, y	rectangular coordinates components (m)
z	number of center points (–)

Greek symbols

α_0	average of the results of the replicated center point (–)
$\alpha_1, \alpha_2, \alpha_3$	main half-effects of the coded variables A, B and C (–)
$\alpha_{11}, \alpha_{22}, \alpha_{33}$	squared effects (–)
$\alpha_{12}, \alpha_{13}, \alpha_{23}$	two factor interaction half-effects (–)
α	thermal diffusivity of fluid (m^2 s^{-1}) ($=k\rho^{-1}c_p^{-1}$)
λ	channel aspect ratio ($\lambda = \frac{a}{H}$)
φ	volume fraction (–)
θ	dimensionless temperature
ρ	fluid density (kg m^{-3})
μ	fluid dynamic viscosity (kg m^{-1} s^{-1})
υ	fluid kinematic viscosity ($=\mu / \rho$) (m^2 s^{-1})

Subscripts/superscripts

ave	average (–)
eff	effective (–)
f	base fluid (–)
in	inlet (–)
p	particle (–)
s	solid (–)
w	wall (–)

number and amplitude of the wavy wall rather than the wavelength. Yang et al. [8] studied the nanofluid flow and heat transfer characteristics in a wavy channel. They showed that the local friction coefficient for the nanofluid increases by increasing the wall wave amplitudes.

Furthermore, many researchers have studied nanofluid convective heat transfer in different geometries [9–11]. Bovand et al. [12] increased the heat transfer rate around a triangular obstacle by adding nanoparticles to the base fluid and change in orientations of the obstacle. They found that the maximum effect of nanoparticles on increment of heat transfer is related to the side facing obstacle and the minimum is belonged to the vertex facing. Rashidi et al. [13] optimized this problem by response surface methodology to calculate the optimum parameters for the maximum heat transfer rate and the minimum drag coefficient. They observed a good agreement with maximum error of 1.3% between the CFD results and predicted results by response surface methodology.

The literature survey showed that many experimental and numerical researches have been performed on nanofluid flow and heat transfer in a wavy channel due to potential of the better heat transfer performance. Beside this advantage of nanoparticles and wavy wall, it has also negative effects on powering cost. For this reason, a sensitivity analysis is crucial from the viewpoint of energy management for such technological to determine how much changes in governing variables will change the heat transfer rate and powering cost. No study has yet performed for such analysis. Therefore, this paper focuses on the thermal and hydraulic managements simultaneously for nanofluid flow inside a wavy channel by a sensitivity analysis.

1.1. Problem statement

The geometry and coordinate systems of the problem are shown in Fig. 1. As shown in this figure, a sinusoidal-wall channel with the length "L" and height "2H" is considered. The Cu-water nanofluid flows inside the channel with inlet developed velocity and constant temperature (T_{in}). The channel is consists of three parts (start and end sections with smooth and adiabatic walls and mid-section with wavy and constant temperature wall (T_w)). The wavy wall has a wave amplitude "a" and wavelength "L_w".

The following assumptions are made to simulate this problem:

- The flow is two dimensional, incompressible, steady and laminar.
- The numerical simulation are performed for the range of Reynolds number $300 \le Re \le 600$, solid volume fraction $0.01 \le \varphi \le 0.05$, channel aspect ratio $0.1 \le \lambda \le 0.3$ and a fixed value of wavelength $L_w = 2H$.
- The sinusoidal wavy curve function is calculated by:

$$S(x) = -H - a\sin\left(\frac{\pi(x-X_1)}{H}\right), X_1 = 3H<x<X_2 = 15H. \qquad (1)$$

2. Mathematical model

2.1. Computational fluid dynamics part

2.1.1. Governing equations

Governing equations to simulate this problem are included the conservation of mass, momentum and energy equations. These equations are utilized in the following forms for this problem:

Conservation of mass equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0. \qquad (2)$$

Momentum equation in x and y directions [14,15]:

$$\rho_{eff}\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu_{eff}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right), \qquad (3)$$

$$\rho_{eff}\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu_{eff}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right). \qquad (4)$$